ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF
ECONOMIC GEOLOGISTS

VOL. 44 DECEMBER, 1949 No. 8

THE PROBLEMS OF COAL GEOCHEMISTRY.[1]

HORACE P. MILLER.

ABSTRACT.

1. Research work in the field of coal geochemistry (being any chemistry bearing on the geological process of coal formation) is briefly sketched —emphasis being placed on work now in progress in the United States. No effort is made to treat any phase of the subject at length; the purpose being, rather, to bring to the attention of geologists work of fundamental importance now being investigated largely by coal chemists.
2. The determination of the chemical constitution of coal is being investigated by treating coal by certain techniques familiar to the chemist in other fields of organic chemistry—*e.g.*, oxidation, reduction, halogenation, thermal decomposition.
3. Work has been done on the process of coalification by the production of artificial coals from specific plant materials and on several of the biochemical aspects of the coal formation problem.
4. Investigations of the physical properties of coal which bear on its chemistry are in progress—particularly in the laboratories of the British Coal Utilization Research Association.
5. The suggestion is made that geologists interest themselves in this branch of coal science. Because of the geologist's intimacy with the descriptive side of the world's coal, it is felt that field studies could be supplemented by determinations of certain properties of coal, the theory of which is now being investigated. It is believed that an ultimate understanding of the metamorphic process of coal formation may involve a knowledge of phenomena that, for the most part, transcends the present interests of both the chemist and the geologist. The cooperation between the chemist and the geologist is regarded as important and every effort should be made to bridge the gulf that appears to exist between the terminology and objectives of the two sciences.

THE task of reporting progress in the field of coal geochemistry—that is, the chemistry bearing on the geological process of coal formation—is a somewhat difficult undertaking for several reasons. First, the boundaries must include a vast territory ranging from studies of the original plant materials, such as lignin, that enter into the formation of coal, to the degradation products ob-

[1] Presented before the Society of Economic Geologists, Committee on Coal Research, New York Meeting, November, 1948.

tained from experimental operations on coal—such as those of oxidation reactions. Secondly, while the name geochemistry implies that geologists and chemists collaborate in the investigation of any and all phenomena within the broad boundaries of the field, I believe that I may state with some certainty that little if any uniformity of opinion exists in regard to the segregation of responsibilities between the chemist and the geologist. Thirdly, a gulf appears to exist between the terminology and the objectives of the two sciences which makes the collaboration mentioned above somewhat difficult to achieve.

Since there are certain large problems in the investigation of coal in which purely chemical considerations are involved (even though ultimately many must pass geological scrutiny) the chemist may walk with a proprietary air over extensive precincts of the field, just as does the geologist in his undisputed areas. There is ample reason to believe, however, that a large penumbra zone exists between the purely chemical and the purely geological areas that must necessarily be studied in the light of both sciences. Thus in this paper, written by one whose training has been that of a geologist, I propose to discuss the problems of coal geochemistry with particular reference to the geologists' obligations and with further regard to the possibility of collaboration between the two sciences of geology and chemistry.

In the present paper detailed consideration cannot be accorded any single phase of the many subdivisions of the subject. Rather than to attempt to cover any one comprehensively, I have chosen to sketch, in the briefest possible way, the several varieties of investigation, with particular reference to work under way in this country (in accordance with instructions of the SEG Coal Research committee). I have further given special considerations to problems bearing on geochemistry suggested at one time or another during sessions of the SEG Coal Research Committee, including those listed by Cady (4).[2]

While the number of problems for investigation by either the chemist, the geologist, or the two in collaboration is admittedly large, for the purposes of this paper a few examples have been chosen and grouped under the headings of chemical constitution of coal, chemical aspects of coal formation, and physical properties of coal that bear on its chemistry. In a few cases, some background material is given for the purpose of emphasizing the potentialities of the problem for further investigation. In other instances problems are suggested without elaboration, but with the hope of arousing interest in further research.

CHEMICAL CONSTITUTION OF COAL.

From the chemists' standpoint, the structure of coal is generally considered to be that of a condensed complex that is either polymeric (12) or similar to a polymer, with the exception that there may not be the complete regular repetition of like units that characterize true polymers. The chemical structure is further considered to be largely aromatic—that is, made up of cyclical structures of which the familiar benzene ring is an example—and the degree of aromatization appears to increase as one proceeds up the scale of rank until ultimately complete aromatization in graphite is reached. The general

[2] Numbers in parentheses refer to Bibliography at end of paper.

picture is that of a group of interlocked rings with bridging members whose nature is largely unknown, but which are in all probability aliphatic groups. The position of nitrogen is far from clear, but may exist as regular members of the polymeric units, or trivalent nitrogen may merely replace carbon here and there in the aromatic nuclei. The chemists have been able to build up a considerable body of evidence to support this concept of coal structure and some headway is being made in a line of research that may eventually lead to a knowledge of the fundamental chemical constitution of coal.

Studies by Means of Oxidation Reactions.—Of the several ways in which the constitution of coal may be investigated, the method of oxidation is probably the one that has produced the most interesting results. When coal is treated in a mild way with oxidizing agents such as permanganate, oxygen, nitric acid, concentrated sulphuric acid, etc. (11, 24, 25), "humic acids" are produced. These substances are similar, but probably not identical with substances present in soils and peat that have been under investigation for over 160 years (47). When one considers Waksman's statement (47) that "After a century and a half of intensive study, our knowledge of the chemical nature of humus and its constituent groups, including the 'humic acids,' is still in a highly confused state," it is not surprising that little headway has been made in identifying the compounds in this category obtained from coal.

Some work has been done on the determination of the average molecular weight of the "humic acids" by a number of methods. Smith and Howard (32) found molecular weights of from 250 to 350 using the method of cryoscopic measurements in solvents such as catechol. Yohe (54) has questioned these low values and has suggested the possibility of chemical degradation taking place in the phenolic solvent, and further has pointed out that other properties (*i.e.*, solubility, lack of volatility, melting point behavior, etc.) are in line with higher molecular weights than those reported. The "humic acids" are known to be alkali soluble, acid insoluble and are far from homogeneous, differing in molecular weight and point of attachment of functional groups.

Because of the complexity of these substances and the difficulties experienced in working with them, oxidation is allowed to proceed beyond the "humic acid" stage to a point where water-soluble acids of medium molecular weight are produced and which are capable of being identified. Notably present in the product of this process are the benzene-carboxylic acids of the mellitic acid type. After these products have been thoroughly understood and identified, progressively more complicated substances produced by less rigorous or less prolonged oxidation may be studied and identified with the backlog of knowledge obtained through the study of their degradation products. In time, one should be able to work back to the "humic acids" and thence to the original coal structure. In the United States, work on the controlled oxidation of coal is being conducted at the Coal Research Laboratory of the Carnegie Institute in Pittsburgh, the Mineral Industries Experiment Station of Pennsylvania State College and at the Illinois Geological Survey in Urbana, Illinois.

Studies by Means of Reduction Reactions.—Most of the literature on coal reduction is concerned with high-pressure catalytic hydrogenation of coal for technical purposes and because of the drastic thermal decomposition is of

limited value in coal geochemistry (49). However, some work has been done on mild reduction of coal in which products that reflect the original structure of coal are produced. The method of attack resembles that with oxidation studies, in that simple compounds are studied first with the ultimate objective of understanding the complex polynuclear structures in coal.

Extended consideration of this type of operation is not appropriate here, but a paper by H. B. Charmsbury and C. C. Wright is mentioned as an example of work of this type under way at Pennsylvania State College (5). To understand the mechanism of hydrogenolysis of coal, pure organic compounds of increasing complexity are studied with the goal of understanding those of the complexity of the coal structures. The paper mentioned is concerned with the hydrogenolysis of abietic acid, a moderately complex organic acid of known structure (Fig. 1).

Also should be mentioned the work in the hydrogenation of petrographic constituents which has been carried out over a period of years by the U. S. Bureau of Mines and other institutions. It is to be expected that, with the present prominence of the coal to liquid fuel problem, efforts in the entire interesting field of the chemical response of specific petrographic ingredients will be pushed to fruition. I have been informed that in work at the Bureau of Mines particular emphasis is to be placed on fundamental coal constitution problems, which is grist for the coal geochemists' mill.

Studies by Means of Thermal Decomposition.—A vast literature exists on the thermal decomposition of coal, which includes solvent extraction, vacuum distillation, and low and high temperature distillation.

Of these, solvent extraction, because of the mild pyrolyzing effect, is of the greatest interest. It is to be expected that the products obtained by extraction would be similar to the original coal except in molecular size. It cannot be assumed, however, that the extract substances appear as such in the original coal. The reasons for this, aside from the evidence from oxidation and reduction studies, are discussed briefly by H. H. Lowry (15) and will not be discussed here except to say that Kiebler, in a fine series of experiments, has established a statistical correlation between the amounts of extract at a given temperature and the internal pressures of the solvents used. It is evident that this is basic information for determining the molecular forces in coal.

In general, it may be said that because of the relatively small yield of extract with solvents that solvent extraction does not reveal as much about the molecular configuration of coal as do other methods. However, several interesting things have been determined from extraction work. For instance, the relatively large proportion of hydrocarbons in the extract indicates that that part of the coal structure containing the least oxygen is least firmly bound in the coal molecule.

Further information is obtained from vacuum distillation of coal. Juettner and Howard (13) have produced substantial evidence of the polymeric nature of coal by distilling Pittsburgh bed coal from the Edenborn Mine at temperatures up to 620° C at pressures of 10^{-2} to 10^{-3} mm. They report that "Even under the most favorable conditions, condensable products are not obtained

from the Pittsburgh coal bed until such temperatures are reached that gas evolution is considerable, so that presumably the products obtained are the result of thermal decomposition. If there are 'free' chemical individuals in this coal, their vapor pressure is so low that no appreciable amount can be distilled in experimental time" (13).

Studies by Means of Halogenation Reactions.—To the knowledge of the writer, no specific studies of the halogenation reactions of coal are in progress today, although they have been used in the past and may today be used in connection with other work to determine the degree of unsaturation of an organic compound.

An extensive investigation of the reactions of a bituminous coal with chlorine and bromine was carried on by J. F. Weiler at the Coal Research Laboratory in Pittsburgh and his results were published in 1936 (50).

In Weiler's summary of halogenation reactions with coal in the "Chemistry of Coal Utilization" he points out that they indicate, as do oxidation and reduction experiments, that the carbon in coal is in condensed ring systems and that ring systems are largely saturated—that is, naphthenic. Further, coal structures are made up largely of six membered rings, and little has been learned regarding the nature of the oxygen linkages.

CHEMICAL ASPECTS OF COAL FORMATION.

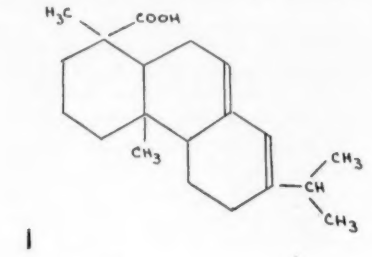
Investigations of the Coalification of Specific Plant Materials.—The literature on coal formation, examined historically, leads one to conclude that after a considerable period of conjecture on the mechanism of coal formation, the workers in the field have settled down to a systematic accumulation of precise data on the minutiae of the problem and are content to wait until enough information has been collected to substantiate any overall theory. In general, it is difficult to argue with this scheme. However, there are, I believe, several problems that may be profitably investigated, even though we may not, for instance, know the precise chemical structures of such materials as the lignins on the one end of the process, or of coal on the other.

There are three principal theories that have been proposed to account for the formation of coal: the lignin theory, the cellulose theory, and a theory proposed by Terres that credits the action of microorganisms with a particularly important role in the process.

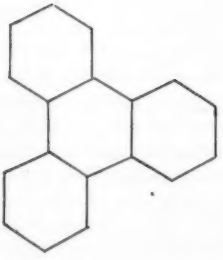
The lignin theory has probably enlisted the greatest number of supporters, for reasons that may be summarized as follows: 1. Lignin is known to be resistant to decomposition by microorganisms, while cellulose is known to be readily converted to carbon dioxide, methane, and aliphatic acids under the conditions usually postulated to exist during the formation of coal (48). 2. The structure of lignin is known to be aromatic, while that of cellulose is not, being according to the familiar Haworth formula made up of a chain of 5,000 to 10,000 glucose molecules. 3. A plausible mechanism has been proposed which traces the chemical steps from lignin to alkali insoluble humus, and thence to coal (6).

The cellulose theory supposes that cellulose is not destroyed and that aromatization takes place and units are produced that condense to form coal.

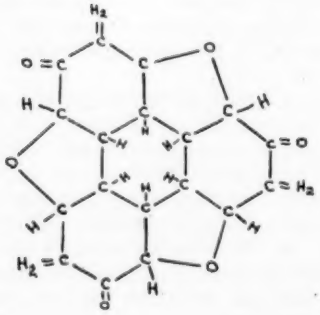
Most theories crediting cellulose with a role in coal formation also include lignin in the process. Berl et al. (1, 2) produced "artificial" coal from cellulosic and lignitic materials by treating them at high pressures and at temperatures from 200 to 350° C. If the material was high in lignin and low in cellulose, coal-like material was formed that suggests that coals of non-coking character may have such a parentage. If the material was low in lignin and high in cellulose, coal-like material was formed that suggests coals of high bitumen content and good coking properties may derive from such a mixture.



1



2



3

FIGS. 1, 2 and 3.

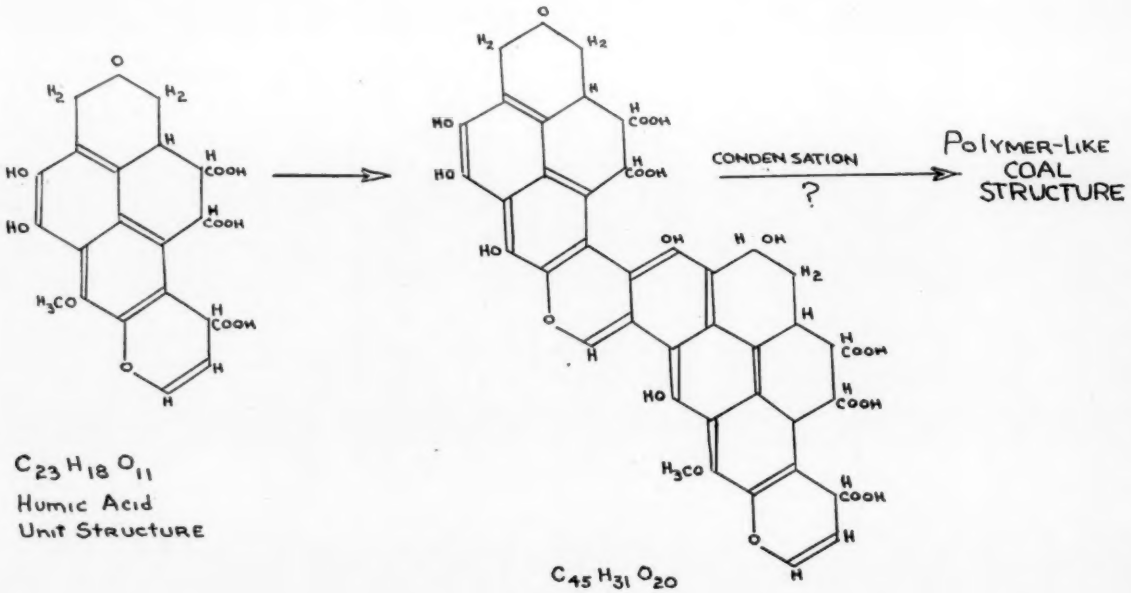

CONDEN SATION
?
Polymer-Like
COAL
STRUCTURE
C23 H18 O11
Humic Acid
Unit Structure
C45 H31 O20

FIG. 4.

The objection of the non-aromatic nature of cellulose is rendered less serious by demonstrations that aromatization of cellulose may be accomplished. Smith and Howard (33) heated pure cotton cellulose at 190 to 400° C and after exhaustive oxidation of the residues from pyrolysis with alkaline permanganate were able to extract water soluble aromatic acids. The percentages of extract ranged from 4.7 percent from the residue at 190° to 32.8 percent at 400°.

Hawley and Harris (10) showed that a lignin-like material may be formed from cellulose under conditions of temperature and pressure that might be expected to exist during coal formation.

Lowry, in one of his excellent summary papers (15) on recent coal chemistry, cites the work of Schrauth (27), who did work on the products obtained by Willstatter and Kalb (51) by reduction of lignin, cellulose and other carbohydrates. One of the main products obtained had the structure shown in Figure 2. Schrauth has further suggested a "parent" molecule for coal having the structure shown in Figure 3.

It is interesting to compare Schrauth's parent molecule with that of Fuchs' (8) as shown in Figure 4.

Any detailed discussion of the relation of recent investigations to the above illustrated concepts of a "parent coal molecule" is beyond the scope of this paper and ability of the author. These examples of postulated coal building blocks are included here largely for the purpose of illustrating, in a general way, the concept of coal held by some chemists. It need scarcely be mentioned that there is much to be done along this line. For instance no account is taken of the nitrogen in coal, which, as mentioned previously, may replace carbon here and there or may be a regular member of the polymer-like molecules. Again, as will be mentioned later, the possibility of other distinct condensed systems involving nitrogen and complementing those of the type illustrated does not appear to be excluded. Finally, the parent molecules suggested seem to lend themselves to condensation early in the process of coal formation to a chicken wire network of rings. Many workers feel that, at least in the early stages, bridging members, including aliphatic groups are indicated.

It is only an occasional worker, like Berl and Terres, who chooses to work on coal formation as a whole, realizing that, in the absence of the precise data now being assembled on the periphery of the problem, their work may be somewhat empirical. Apparently very little work of this type is under way today, although it is the writer's opinion that experimental coalification studies supplemented by field and laboratory investigations of the degree of coalification of plant constituents—particularly in the lower coals—should be of great value to coal geochemistry. Also, it is self-evident that certain work in soil science closely parallels work in coalification and despite the fact that differences by virtue of the aerobic conditions of one and the essentially anaerobic conditions of the other exist, a program of research set up on the pattern of, for instance, that of certain work in the Soils Division of the U. S. Department of Agriculture's Bureau of Plant Industry might be a satisfactory approach to some phases of the problem.

Investigations on the Advancement of the Rank of Coal.—The concept that advancement of coal rank is a function of the degree of aromatization of the coal molecules suggests that experimental operations promoting aromatization might yield interesting information regarding coal formation. While much of the evidence for or against such a concept must necessarily be beyond the scope of this paper—involving metamorphic processes attendant to coal formation, temperatures experienced, etc.—there are certain considerations of a chemical nature that may be mentioned.

It should be emphasized that any laboratory demonstration that coal can be advanced in rank by application of pressure or heating is not positive evidence that the geological process followed the same pattern. In the case of anthracite the evidence is good that it was derived from high-rank bituminous coal through the agency of metamorphic processes. Turner (46), for instance, has shown that Pennsylvania Anthracite and High Rank Bituminous coals are almost exactly alike in morphological constitution and that their differences are explainable in terms of metamorphic reconsolidation.

But when we consider the coals of bituminous and lower rank, the evidence of rank advancement is subject to question. Berl's contention that differences in rank may be explained in terms of differences in original plant ingredients has been mentioned (1, 2). Taylor (36) has conjectured that the conditions necessary for the formation of peat, lignite, and higher rank coals are different depending on the acidity of the environment and non-organic constituents of the roof material. Finally, Fuchs (7) in an exceedingly interesting paper on the relation of the thermodynamics to coal formation, states that

> the presence of hydroxyl and carboxyl groups in brown coals and lignite is evidence that oxidation processes were essential in transforming the original plant material into these fuels. The absence of these groups in bituminous coals and anthracites and their lower oxygen content indicate the importance of reduction processes in the formation of higher rank fuels. While lignites may have been reduced to give bituminous coals and anthracites, the simpler way is obviously that the original plant material underwent reduction without passing through a lignite stage.

That a great opportunity for both laboratory and field inquiry is present in this phase of the subject of coal geochemistry is, I believe, quite evident.

Bacteria as an Important Agent in Coalification.—There are so many ramifications to this problem that to attempt any discussion under the restrictions of this paper is impossible. The question of the nitrogen content of coal and the extent of the role of bacteria in coalification leads one naturally into the whole subject of plant and animal proteins—which needless to say is one of the important fields of investigation in biochemistry. Since, however, an understanding of the part played by bacteria in coalification is so important, some mention of a few of the many attacks on the problem published in the literature seems justified.

The relatively high percentage of nitrogen when compared with that of most plants led Terres (45) to conjecture the agency of bacteria as a major factor in coalification, since the nitrogen content of bacteria runs up to 13 percent. Investigations in the production of artificial coals showed that the

coal-like substance formed had a higher nitrogen content than the peat sludge with which he started. This he attributed to the bacterial contribution, and on this basis, has developed an ingenious theory of coal origin.

In connection with this work should be mentioned the early work of Gottlieb (9) and of Maillard (21), who showed that amino acids derived from either plant or animal proteins could react with monoses formed from polysaccarides, pectins and cellulose by decomposition, to form the so-called melanoids, which are complex condensation products resembling humic acids, and which may have an important bearing on coalification.

In addition to the problems discussed briefly above, the following problems are listed which are, in the opinion of the writer, particularly interesting for further study (including several proposed by Cady (4)).

1. Thermodynamics and coal formation (7). In this connection, the field of study should be broadened to include the whole process of metamorphism. By applying thermodynamic reasoning to the problem, we acquire a more precise control than is otherwise possible. The organic material having undergone vicissitudes that are largely metamorphic, may be thought of as having attained various levels translatable into the language of thermodynamics.
2. The role of waxes and resins in coalification.
3. Chemical interaction between coal and roof-floor materials.
4. Fusain and fusainization.
5. Source and occurrence of interstitial "colloidal" substance in coal, particularly in vitrain.
6. Nature and causes of the reducing environment accompanying coalification.
7. Role of proteins and the origin of nitrogen in coal.

PHYSICAL PROPERTIES OF COAL.

Up to this point, I have briefly touched on some of the fields of investigation in coal chemistry in which coal is subjected to largely chemical operations to determine its constitution and possible mode of formation. From a geologist's standpoint, it is interesting that a coal structure should be postulated that transcends the boundaries of the distinct entities that the petrographer has seen and described. For instance, examined microscopically, the waxes and resins appear to have emerged from the process of coal formation relatively unchanged or as shown by Schopf (29) to have altered much more slowly than other constituents. Biggs (3), however, has shown by investigating the degradation products obtained from both "humins" and the so-called "bitumens" that identical treatment produces very similar products. Also, Stadnikoff and Titov (34) have shown that the bitumens produce, in addition to simple compounds, some high molecular weight polymerization products in the formation of peat. The chemist is thus approaching the view that petrographic differences are not of the same transcendental importance in coal chemistry that they are in coal geology.

It may develop, after all the scientific returns are in, that several condensation types prevail in the lower coals and that as one proceeds up the scale of rank the progressive aromatization obscures the differences until, as in the case of graphite, homogeneity prevails. The application of techniques sepa-

rate from those of the purely chemical may throw light on the subject. Just as the geologist has added to his equipment the microscope, so may he adopt other tools to study coal and to extend and refine his investigation of coal entities. Many of the differences of opinion concerning the nature of coal probably arise from lack of precise data that are the geologist's obligation to provide.

Without entering here into the somewhat futile discussions current today of just what specific training is required of a man to perform certain tasks ahead in coal geochemistry, it is the writer's opinion that techniques, such as those to be mentioned in the following section on Physical Properties of Coal, are of a particular interest to the geologist. Because of the geologist's intimacy with the descriptive side of the world's coal, it may be assumed that a broadening of the field of geological inquiry to include investigations into such subjects as electrical, magnetic, optical, thermal, etc., properties of the whole range of the world's coal is desirable.

Optical Properties of Coal with Particular Reference to the Formulation of a Petrographic System Which Has Chemical Significance.—Ideally, a link between the work of the geologist and the chemist should exist, so that the results obtained by one science may be understood in the language of the other. The classification of coal by the petrographer, whether it be the vitrain-clarain-durain-fusain classification of Stopes or the anthraxylon-attritus classification of Thiessen, can be used for the usual purposes of the petrographer, but it fails to link with work of the chemist.

Numerous attempts have been made to devise such a classification and a study of the literature will show that the absence of a generally accepted scheme is not the result of lack of trying. One of the most interesting attempts has been that of Seyler (30), whose most recent work deals with the correlation between reflectivity and coal composition. Previously (31) he had devised the well-known volatile-displacement-hydrogen classification in which coals were plotted according to these factors and were found to fall generally within triangular limits with the vertices corresponding to assumed composition of the pure macerals vitrinite, exinite and fusinite. By careful measurements of the percentage of light reflected from the surface of small areas of the coal constituents, Seyler has shown that there are apparently discontinuities in reflectance and his so-called "Mean Reflectance" can only assume some nine distinct values. He has further shown that the value for any given maceral will be stepped up by "a sudden jump or mutation" as one proceeds up the scale of rank. As Dr. W. A. Wooster of Cambridge has remarked (52) in discussion of Seyler's work, "It is probable that the study of coal would develop most rapidly if further work could be done on homogeneous material of a given reflectance number."

In the United States, McCabe and Quirke (20), using vitrain from Illinois Coal, showed that rank may be correlated with refractive index. In connection with this work, by way of emphasizing its importance, it is interesting to quote Lowry's statement (made in discussion of McCabe and Quirke's paper) that "In studying the products of mild hydrogenation of coal at the Coal Research Laboratory, we found the refractive indices of condensed ring

compounds to be related to chemical structure, the pure aromatic type having the highest refractive index, with the hydroaromatic type lying between the aromatic and aliphatic types. Refractive index is related to carbon-hydrogen ratio, the condensed aromatics, in which the ratio is highest, having the highest refractive indices."

Investigation of Other Physical Properties of Coal.—Just as rather striking results may be assumed to result from work on the reflectance and other optical properties of coal, so may we expect important contributions through the study of other physical properties of coal, *i.e.*, that the material under study is not destroyed, and thus we do not have to extrapolate from our findings to project back to the original coal.

Examples of properties of coal now under study, particularly in English laboratories, include: a. Magnetic properties; b. Electrical properties; c. X-ray studies of coal structure; d. Adsorptive and colloid properties; e. Infra-red studies of coal, etc.

As an illustration, "blackness" and electrical conductivity really measure the extent to which some electrons can move and this depends on the nature of the condensation in the structure. Or, as a further illustration, Wooster (53) has suggested that a study of the magnetic properties and the chemical composition of the same piece of coal afford a method of assessing the aromatic content of the coal.

Anyone who has witnessed the significant contributions of the above techniques to the study of other substances can appreciate their value in coal studies. Since so much is yet to be learned, it seems proper that one need not be too concerned about "where they may lead." We may proceed, however, with the assurance that the information gained will be important and possibly vital to a full understanding of the outstanding problems of coal geochemistry.

AYRSHIRE COLLIERIES CORPORATION,
INDIANAPOLIS 4, IND.,
July 8, 1949.

BIBLIOGRAPHY.

1. Berl, E., and Keller, H., Petrographische und Chemische Untersuchungen zum der Enstehung der Kohlen: Liebigs Ann., Bd. 501, S. 84–106, 1933.
2. Berl, E., and Schmidt, A., Über die Enstehung der Kohlen, II: Liebigs Ann., Bd. 493, S. 97–152, 1932.
3. Biggs, B. S., The relation of extract to residue in a bituminous coal: Am. Chem. Soc. Jour., vol. 58, pp. 1020–1024, 1936.
4. Cady, G. H., Report of the committee on research on coal of the Society of Economic Geologists: ECON. GEOL., vol. 42, no. 5, pp. 509–512, 1947.
5. Charmsbury, H. B., and Wright, C. C., The hydrogenolysis of abietic acid: Am. Chem. Soc. Jour., vol. 66, pp. 526–532, 1944.
6. Fischer, F., Was lehrt die Chemie über die Enstehung und die chemische Struktur der Kohle: Die Naturwissenschaften, Bd. 9, S. 958–968, 1921.
7. Fuchs, W., Thermodynamics and coal formation: Am. Inst. Min. Met. Eng. Trans., vol. 149, pp. 218–223, 1942. (Also Tech. Pub. 1333, 1941.)
8. Fuchs, W., and Daur, R., Neuere Untersuchungen zur Konstitution des Fichtenlignins der Huminsäuren und der Humine: Brennstoff-Chemie, Bd. 12, Nr. 14, S. 266–267, 1931.
9. Gottlieb, Emil, Untersuchung über die elementare Zusammensetzung einiger Holzsorten in Verbindin mit calorimetrischen Versuchen über ihre Verbrennungsfähigkeit: Jour. Prakt. Chemie, Bd. 28, S. 385–421, 1883.

10. Hawley, L. F., and Harris, E. E., Synthetic lignin: Ind. and Eng. Chemistry, vol. 24, pp. 873–875, 1932.
11. Howard, H. C., Chemical constitution of coal—as determined by oxidation reactions: Chemistry of Coal Utilization, ed. by H. H. Lowry, vol. 1, chap. 9, pp. 346–376, Wiley, New York, 1945.
12. Howard, H. C., The polymeric character of a bituminous coal: Jour. Phys. Chem., vol. 40, pp. 1103–1112, 1916.
13. Juettner, B., and Howard, H. C., Pyrolysis of coal: Ind. and Eng. Chemistry, vol. 26, pp. 1115–1124, 1934.
14. Kiebler, M. W., Extraction of bituminous coal: Influence of the nature of solvents: Ind. and Eng. Chemistry, vol. 32, pp. 1389–1394, 1940. (Also Carnegie Coal Research Lab., Contr. no. 87.)
15. Lowry, H. H., The chemical coal: Ind. and Eng. Chemistry, vol. 26, pp. 133–137, 1934.
16. ——, Some chemical aspects of coal utilization: Amer. Inst. Chem. Engrs. Trans., vol. 30, pp. 280–298, 1933.
17. ——, Recent developments in coal research: Proc. 2nd Ann. Coal Conference, pp. 67–85, W. Virginia, 1939.
18. ——, Significance of the chemical nature of coal: Polish Inst. Arts. Sci. America Quart. Bull., vol. 1, pp. 997–1010, 1943.
19. ——, Accomplishments of the Coal Research Laboratory of the Carnegie Institute of Technology: "Bituminous Coal Research," vol. 6, no. 1, pp. 4–5; no. 2, pp. 4–5, 1946.
20. McCabe, L. C., and Quirke, T. T., Angle of polarization as an index of coal rank: Am. Inst. Min. Met. Eng. Trans., vol. 130, pp. 445–455, 1938.
21. Maillard, L. C., Action des acides aminés sur les sucres; formation des mélanoïdines par voie méthodique: Acad. Sci. Paris Comptes rendus, t. 154, pp. 66–68, 1912.
22. ——, Formation d'humus et de combustibles minéraux sans intervention de l'oxygène atmosphérique, des microorganismes, des hautes températures, ou des fortes pressions: Acad. Sci. Paris Comptes rendus, t. 155, pp. 1554–1556, 1912.
23. ——, Origine des bases cyclique du goudron de houille: Acad. Sci. Paris Comptes rendus, t. 157, pp. 850–852, 1913.
24. Menzel, A., Literatur über der Einwirkung chemische Agentien an Kohlen und Kohlenstoff II: Abh. Kenntnis Kohle, Bd. 9, S. 308–338, 1930.
25. Niggemann, H., Literatur über der Einwirkung chemische Agentien an Kohlen und Kohlenstoff: Abh. Kenntnis Kohle, Bd. 1, S. 1–20, 1915–1916.
26. Proc. Conference on ultra-fine structure of coals and cokes: British Coal Util. Res. Assoc., 1944.
27. Schrauth, Walther, Zur chemischen Struktur des Lignins und der Kohle: Zeitschr. angew. Chemie, Jg. 36, Nr. 70, S. 571, 1923.
28. ——, Über die chemische Struktur der Kohle: Brennstoff-Chemie, Bd. 4, Nr. 11, S. 161–164, 1923.
29. Schopf, J. M., Variable coalification: Econ. Geol., vol. 43, pp. 207–225, 1948.
30. Seyler, C. A., Petrology and the classification of coal. I and II: Coll. Guard., vol. 155, pp. 990–994, 1046–1048, 1087–1089, 1137–1139, 1231–1233, 1937.
31. Seyler, C. A., The relevance of optical measurements to the structure and petrology of coal: Reference number 26, pp. 270–289.
32. Smith, R. C., and Howard, H. C., Equivalent and molecular weights of humic acids from a bituminous coal: Am. Chem. Soc. Jour., vol. 57, pp. 512–516, 1935.
33. Smith, R. C., and Howard, H. C., Aromatization of cellulose by heat: Am. Chem. Soc. Jour., vol. 59, p. 234, 1937.
34. Stadnikoff, G., and Titov, N. G., Zur Kenntnis der Torfbitumina: Brennstoff-Chemie, Bd. 9, S. 357–358, 1928. Also Zhur. Priklad. Khim., vol. 1, pp. 328–330, 1928. Cited by Kiebler in "The action of solvents on coal": Chemical Utilization of Coal, vol. 1, chap. 19, p. 687, Wiley, New York, 1945.
35. Stadnikov, G., Die Entstehung von Kohle und Erdöl: Schriften aus dem Gebiet der Brennstoff-Geologie (O. Stutzer), H. 5–6, 254 pp., Stuttgart, 1930.
36. Taylor, E. McKenzie, Base exchange and its bearing on the origin of coal: Fuel in Science and Practice, vol. 5, no. 5, pp. 195–202, 1926.
37. ——, The decomposition of vegetable matter under soils containing calcium and sodium as replaceable bases: Idem, vol. 6, no. 8, pp. 359–367, 1927.
38. ——, The replaceable bases in the roofs of bituminous coal seams of Carboniferous age: Idem, vol. 7, no. 2, pp. 66–71, 1928.
39. ——, The replaceable bases in the roofs of bituminous coal seams of Cretaceous age: Idem, vol. 7, no. 3, pp. 127–128, 1928.
40. ——, The replaceable bases in the roofs of bituminous coal seams of Tertiary age: Idem, pp. 129–130.

41. ——, The conditions and geologic evidence of base exchange between the roofs of bituminous coal seams and solutions of sodium chloride: Idem, pp. 130–134.
42. ——, The replaceable bases in the roofs of lignite seams: Idem, vol. 7, no. 5, pp. 227–228.
43. ——, The replaceable bases in the roofs of anthracite seams: Idem, pp. 228–229.
44. ——, Base exchange and the formation of coal: Idem, pp. 230–238.
45. Terres, E., Contributions to the origin of coal and petrography: Proc. 3rd Conf. Internat. Conf. Bit. Coal, vol. 2, pp. 797–808, 1931.
46. Turner, H. G., Constitution and nature of Pennsylvania anthracite with comparisons to bituminous coal: Am. Inst. Min. Met. Eng. Trans., Coal Division, pp. 627–643, 1930.
47. Waksman, S. A., Humus, Bibliography, pp. 413–480, Williams & Wilkins, Baltimore, 1936.
48. Waksman, S. A., and Stevens, K. R., Contributions to the chemical composition of peat. I. Chemical nature of organic compounds in peat and methods of analysis: Soil Science, vol. 26, pp. 113–137, 239–252, 1928.
49. Weiler, J. F., Constitution of coal—as determined by reduction reactions: Chemistry of Coal Utilization, Ed. by H. H. Lowry, vol. 1, chap. 10, pp. 377–417, Wiley, New York, 1945.
50. Weiler, J. F., Exhaustive chlorination of bituminous coal: Am. Chem. Soc. Jour., vol. 58, pp. 1112–1114, 1936. (Also Carnegie Coal Research Lab., Contrib. no. 42.)
51. Willstatter, R., and Kalb, L., Über die Reduktion von Lignin und von Kohlehydraten mit Jodwasserstoffsäure und Phosphor: Ber. d. Chem. Gesell., Jg. 55, Bd. 3, S. 2637–2652, 1922.
52. Wooster, W. A., Discussion, Ref. 26, p. 316.
53. Wooster, W. A., and Wooster, Nora, The magnetic properties of coal: Proc. Conference on ultra-fine structure of coals and cokes: British Coal Util. Res. Assoc., pp. 322–329, 1944.
54. Yohe, G. R., Personal communication.

ORE DEPOSITS OF THE WALLAPAI DISTRICT, ARIZONA.

BLAKEMORE E. THOMAS.

CONTENTS.

	PAGE
Abstract	663
Introduction	664
Rock types	666
Geologic structure	668
Vein deposits	671
History and production	671
Distribution of veins	672
Primary minerals	673
Paragenesis of the ores	673
General features of oxidation	680
Secondary enrichment	684
Wall rock alteration	684
Vein structure and expression	687
General features of primary deposition	690
Ore shoots	692
Age and genesis of deposits	694
Disseminated sulfide deposit	696
Turquoise deposits	700
Emerald Isle copper deposit	700
Bibliography	703

ABSTRACT.

The Wallapai district is in the Cerbat Mountains, an eastward-tilted fault-block composed of Precambrian metamorphic and igneous rocks that have been intruded by granite porphyry of Tertiary (?) age. Small patches of Tertiary and Quaternary volcanic rocks occur along the flanks of the range.

Mineralization is believed to have occurred after the close of Tertiary volcanic activity. The first phase consisted of "porphyry copper" mineralization in a strongly shattered portion of a granite porphyry stock. This was succeeded by the formation of veins that contain lead-zinc ores. The veins are superimposed upon and grouped symmetrically around the "porphyry copper" mineralization. Tectonic action is postulated as the fundamental control for the emplacement of the granite porphyry stock and for the two types of sulfide mineralization that are areally associated with the stock. Turquoise deposits have developed by supergene processes in the capping of the "porphyry copper" deposit.

A late fault cuts both bedrock and alluvium at the western base of the range. This fault and a surrounding area of the alluvial blanket have been mineralized by chrysocolla to form the Emerald Isle copper deposit. The chrysocolla is believed to be hypogene in this deposit.

INTRODUCTION.

Geography.—The Wallapai district embraces an area of approximately forty-five square miles in the Cerbat Mountains, a fault-rock range six to ten miles wide that extends northward from Kingman, Arizona for a distance of thirty miles. The range is bordered on the west by the Sacramento Valley and on the east by the Hualpai Valley. The mineralized portion of the range is in the Chloride quadrangle (Fig. 1), which is within and close to the eastern border of the Basin and Range Province and is part of the "mountain region" of Arizona. The "mountain region" is a northwest trending belt defined by Ransome (39)[1] as adjoining the Colorado Plateau region on the northeast and the "desert" region on the southwest (Fig. 1).

The mineralized area is an elongate zone that is oblique to the trend of the Cerbat Range, so that it spans the range to the south but is confined to the western flank of the range to the north. The Wallapai district comprises four contiguous mining areas which, from north to south, are known as the Chloride district, the Mineral Park district, the Stockton Hill district, and the Cerbat district (Fig. 3). Four types of mineralization occur. The principal one is base-metal ore in an extensive pattern of veins that covers all of the mining areas. It is with this base-metal mineralization that the present paper is primarily concerned. A "porphyry copper" type of mineralization occurs in the Mineral Park district, coincident in location with a portion of the base-metal belt. The other types are a unique copper silicate deposit in late gravels and turquoise deposits in the Mineral Park district.

Elevations within the district vary from 3,500 feet to 6,978 feet. The rocks are predominantly granitic and have eroded into a massive rugged topography.

Geological Work.—A thorough reconnaissance of the Wallapai district was made by F. C. Schrader (45). His observations and conclusions regarding the general geology and ore deposits are excellent, and his report still serves as a "bible" for the region. Schrader's report has been the chief source for most of the few short summaries that have been written subsequently. His discussions of the principal mining properties are valuable for their detailed record of early history, development, and production.

E. S. Bastin (3) studied some of the rich silver ores of the district from the standpoint of secondary enrichment. His conclusions concerning the paragenesis of the silver minerals are very useful as those minerals are now extremely scarce in the ore deposits.

The most complete recent summary is that of R. M. Hernon (23). Short papers have appeared in various mining publications from time to time, but they have been restricted to technical mining features or short geological descriptions of single mines and prospects.

The present paper embodies a portion of a Ph.D. thesis submitted to the California Institute of Technology (Thomas, 50) that was based on field work done during the summers of 1941, 1947, and 1948. Grateful acknowledgment is due Professor C. D. Hulin, of the University of California, Berke-

[1] Figures in parentheses refer to bibliography at end of paper.

ley, for his aid in the initial stages of the work and to Professors Ian Campbell and James A. Noble, of the California Institute, for trips they made to the field and for their stimulating supervision and advice in the several phases of

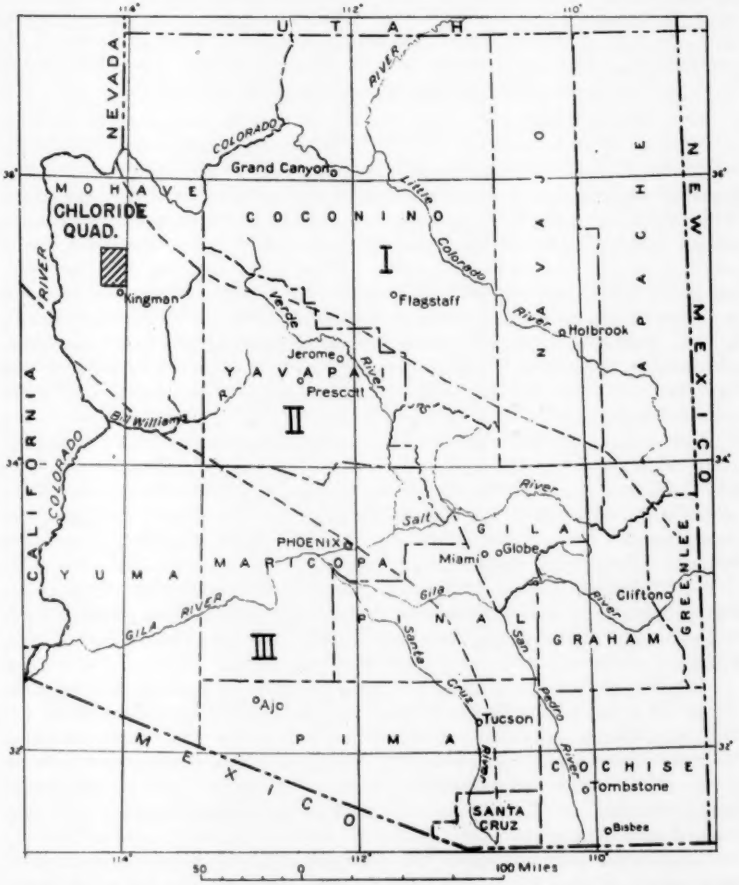


FIG. 1. Index map of Arizona showing location of Chloride quadrangle and Ransome's (1903) physiographic divisions of the state. I—Plateau region; II—Mountain region; III—Desert region.

research and the writing of the paper. Many helpful suggestions were made by Professors R. H. Jahns and C. W. Merriam, of the California Institute, who kindly reviewed the manuscript.

Only a few of the many cordial and interested mining operators and residents of the region can be mentioned. Especially helpful in the prosecution of the field work were Jacob Shoder, W. J. Gardiner, N. A. and W. C. Wimer, Walter Winsett, and T. L. Chapman, all concerned at various times with the operation of the Tennessee-Schuylkill mine; F. J. McEntee, Jr. and D. L. Zlatnik of the Mineral Park Milling Company; Earl Hastings of the Lewin-Mathes Mining Company; and G. Austin Schroter, Oral Nichols, and J. T. Jordan of the Northern Arizona Engineering Company.

ROCK TYPES.

Cerbat Complex.—A basement assemblage of metamorphic and igneous rocks of Archean age, for which the term Cerbat complex is here proposed, forms the bulk of the Cerbat range. The oldest rocks consist of vertical to steeply dipping layers of hornblende-diopside schist and amphibolite, biotite schist, quartzite, and lit-par-lit gneiss. These rocks typically occur together but in no particular sequence. Exposures are numerous but discontinuous, and more abundant granite gneiss surrounds, interleaves, and grades into the layers. However, in several places enough of these layered rocks have been preserved to reveal their disposition in fragments of folds. The folds, as well as evidence of relict bedding in the quartzites, suggest that the layered rocks were originally a series of stratified deposits.

Intrusion of granitic magma either accompanied or followed the folding, and granite gneiss is the predominant rock type in the complex. Perhaps fifty percent of the gneiss is migmatite, whereas the balance is believed to be orthogneiss. The rocks are characterized by diverse texture, ranging from faintly banded types to flaser gneisses that have well-developed "augen" of feldspar. Porphyritic phases are abundant.

Small areas of more mafic gneiss occur in places within the large exposures of granite gneiss. Most hand specimens of these mafic gneisses seem to be dioritic, and quartz gabbro and tonalite have been determined in thin section.

Coarsely porphyritic granite occupies the core of a distinctive anticline preserved in the schists in the western half of the Chloride district (Fig. 2). The name Diana granite is here proposed for it after the Diana (Arizona Magma) mine, which is approximately in the center of the exposure. Similar porphyritic granites occur elsewhere, notably on the east side of the Cerbat range, but this intrusion is the only unit in the Cerbat complex that was mapped separately.

Large white pegmatite dikes are abundant in the Precambrian areas, and thick sheets of pegmatite have been injected between the layers of metamorphic rocks in many places. Aplite or aplitic granite is commonly associated with the pegmatite dikes.

Diabase dikes are also common in the Cerbat complex. The dikes range in width from a few feet to as much as 150 feet, and some can be traced for more than a mile.

Narrow zones of mylonite, trending uniformly northeast, are scattered throughout the complex.

Ithaca Peak Porphyry.—Two intrusions of granite porphyry, within the Cerbat complex but presumably much younger, are exposed along the western flank of the range, one in the Chloride district and the other in the Mineral Park district. They are similar in texture and composition and are assumed to be the same age. Both are here designated Ithaca Peak porphyry, after the imposing crag of that name in the Mineral Park district. The intrusion in the Chloride district is a curved, steeply-dipping sill from 2,000 to 5,000 feet thick that was intruded into the limbs of a large anticline (Fig. 2), whereas the intrusion in the Mineral Park district is a stock that has a roughly circular exposed area 3½ to 4 miles in diameter. Several thick tongues extend out from the southeast side of the stock, the largest reaching a mile and a half through Union Basin to the Golconda mine. In addition to this large sill and stock, numerous dikes and a few small plugs of granite porphyry have invaded the Cerbat complex. Dikes are especially abundant in the Chloride district.

Inasmuch as the granite porphyry is injected into Precambrian schist and gneiss, it might be assigned to almost any geologic period. Schrader (45, p. 30) classified it as late Jurassic or early Cretaceous and considered it to be of the same period of intrusion as the batholiths of California and western Nevada. This is a reasonable comparison, but on the basis of close areal and structural relationships between the Mineral Park stock and the mineralization there may be even more justification for considering the granite porphyry to be Tertiary in age.

Dikes and irregular small masses of granite pegmatite and aplite, apparently derived from the Ithaca Peak porphyry, are scattered through the intrusions. Similar bodies of the same age probably occur in the Precambrian rock areas but cannot be distinguished from the earlier pegmatites and aplites.

A series of lamprophyre dikes was injected after the emplacement of the Ithaca Peak porphyry. Vogesite and spessartite dikes are abundant, and one kersantite dike was observed. The lamprophyres occur in the walls of some veins, typically in multiple-dike association with such rocks as granite porphyry, diabase, and pegmatite.

Teritary Eruptive Rocks.—Volcanic strata probably covered the entire Chloride quadrangle at one time. Remnants occur west of Chloride along the down-dropped side of the Sacramento fault (Fig. 2) and discontinuously along the east flank of the Cerbat range. The oldest eruptive rocks are flows, tuffs, and breccias predominantly andesitic in composition. These rocks rest upon a surface cut on the Cerbat complex. They are here termed the Bull Mountain series, as they form the cap-rock of that peak. Overlying these basal andesites, with apparent disconformity, are rhyolite tuffs, breccias, and flows. They are here designated the Kingman series, as they are best exposed in and around Kingman. West of Chloride, on the north side of the mouth of Big Wash, an andesite flow lies unconformably on rhyolite tuff and breccia of the Kingman series. This "Big Wash andesite" was not observed elsewhere in the area mapped.

These volcanic extrusives have previously been assigned to the Tertiary by Schrader (45, p. 34) and Lee (28, p. 14). There is no proof that all of

them are Tertiary. Lacking evidence to the contrary, however, their inclusion as part of the Tertiary volcanic system so widespread over the Basin and Range Province is believed reasonable.

Numerous rhyolite dikes, some as much as 200 feet wide, and a few small andesite dikes cut both the Cerbat complex and the Ithaca Peak porphyry. It is assumed that the dikes were intruded in Tertiary time as part of the Tertiary volcanic system of the Basin and Range Province.

Quaternary Olivine Basalt.—Unconformably capping most of the mapped exposures of volcanic rocks along the Sacramento fault are sheets of olivine basalt from 10 to 25 feet thick. Portions of the basalt layers rest on and interfinger with Quaternary alluvium, and in one place the basalt seems to lie unbroken across the Sacramento fault. Two basalt dikes were observed which are possibly Quaternary in age and which may have been feeders for the extrusive sheets of basalt.

Alluvium.—Alluvium within the Wallapai district includes the detritus that covers the bottoms of the canyons and washes, terrace deposits that occur along the walls of many canyons, and a pediment veneer along the base of the range. The alluvium consists of a poorly sorted accumulation of angular to sub-rounded sand, pebbles, cobbles, and boulders representing all the rocks of the Cerbat Range. Much of the alluvium can be correlated with the Temple Bar conglomerate of Pleistocene age (28, p. 16).

GEOLOGIC STRUCTURE.

Archean Fold System.—Despite widespread obliteration of older rocks by batholithic intrusion and granitization, evidence of folding exists in several places in the Cerbat complex. All the folding has a uniform northeast axial trend, and much of it seems to be isoclinal. The best preserved fold occurs in the Chloride district, where the disposition of the crystalline metamorphic and igneous rocks in steeply-dipping concordant curved layers reveals the existence of a large northward-plunging anticline (Fig. 2). A smaller but well-defined anticlinal remnant is marked by the distribution of septa in the northwest side of the Ithaca Peak porphyry stock in the Mineral Park district.

Foliation.—Foliation in the Cerbat complex ranges from the excellent flow cleavage of the biotite schists to faintly gneissic granite. Foliation in the anticlinal remnants seems to be parallel to original bedding for it wraps around the noses of the folds. Elsewhere the foliation tends to follow a northeast strike, suggesting formerly extensive isoclinal folds. Most of the foliation is attributed to high-grade regional metamorphism, but in the gneisses some is probably due to primary planar flow, some has been inherited from granitized schists, and some is due to post-consolidation compression.

Primary planar flow structure is well developed in places along the borders of the Ithaca Peak porphyry sill and stock, and compressive forces have formed local areas of gneissic banding within both intrusions. Much of the secondary foliation strikes northeast and has vertical to steep dips.

Joints.—Three joint systems cut all the rocks, without discrimination as to type or age of rock. The strongest system includes joints which strike about northwest and dip very steeply. Minor joints can be grouped roughly

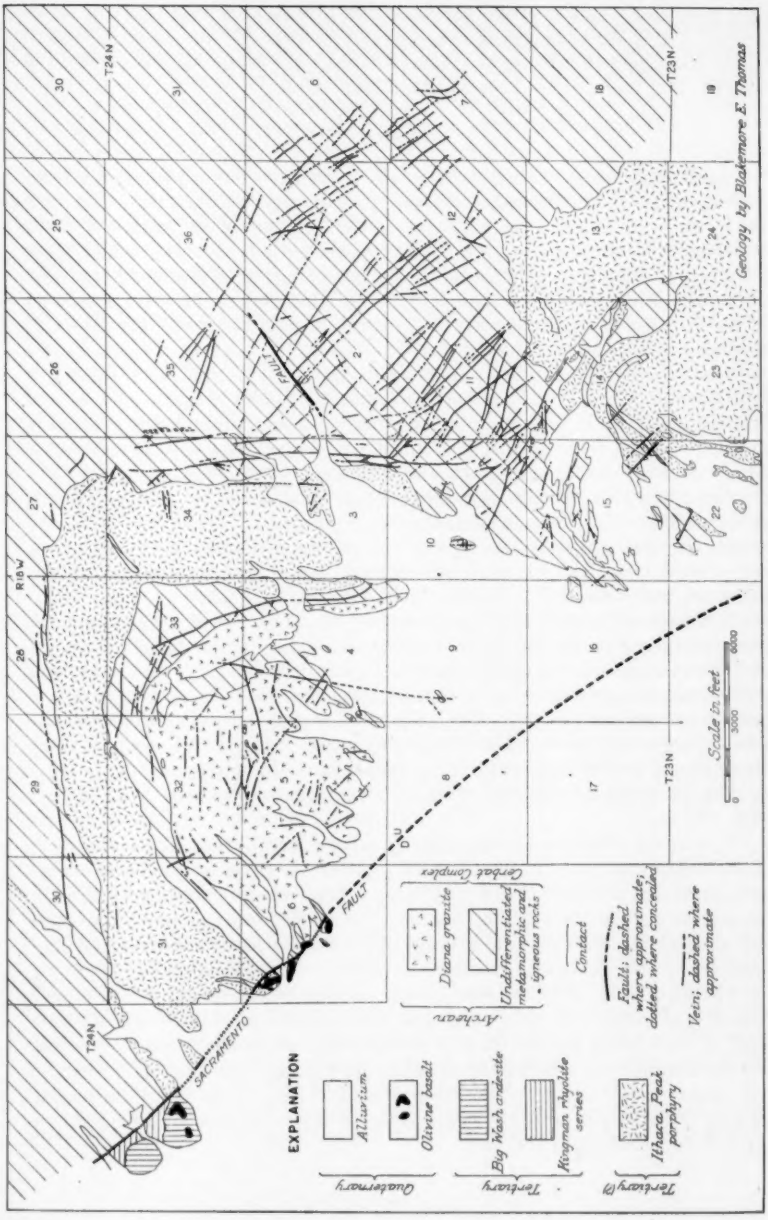


FIG. 2. Geologic map of the Chloride district, Arizona.

into a set that tends to strike northeast and into another that tends to strike north. The joints have served as avenues of injection for numerous silicic and mafic dikes, and the strongest system was a prime factor in determining the location and orientation of the quartz-sulfide veins.

Faults.

Aside from zones of mylonite, which indicate localized intense shearing, faulting of pre-Ithaca Peak porphyry age is undecipherable. Beginning with the intrusion of Ithaca Peak porphyry, however, a number of ages of faulting is evident. Minor dislocations accompanied the periods of injection of granite porphyry dikes, lamprophyre dikes, and rhyolite and andesite dikes. The maximum displacement for any of these was observed in the ridge northeast of the North Georgia mine where a vogesite dike offsets a diabase dike 100 feet horizontally.

Mineralized Faults.—The most obvious faults are those along which veins have formed (Fig. 2). The distribution and attitudes of these mineralized faults is discussed in the section on vein deposits. Striations in the vein walls indicate that the latest fault displacement has almost invariably been oblique. The presence of slickensided surfaces, large amounts of gouge, and rolled and crushed fragments of wall rock suggest that shearing stress was important. Most are believed to be normal faults, but some seem to be reverse. All are steeply-dipping, and in such oblique-slip faults the distinction between normal and reverse movement has little significance, as a change in dip of a few degrees can easily result in a change in classification.

It is impossible to determine the amount of movement in most places. A few mineralized faults offset dikes, however, and a horizontal displacement of 120 feet was measured along a vein that offsets a lamprophyre. No markers were found to determine the amount of vertical movement. Five periods of activity are reflected in the faults. The first was that which opened the fissures and gave access to mineralizing solutions. This was followed by three intra-mineral fracture periods and by post-mineral fracturing.

The mineralized faults are younger than rhyolite and andesite dikes of Tertiary (?) age.

Transverse Faults.—Steeply-dipping intra-mineral cross faults cut some of the veins and have produced small offsets. A large post-mineral transverse fault that strikes N 55° E and is essentially vertical cuts several veins in the eastern part of the Chloride district. Veins that seem to match on opposite sides of the fault indicate a horizontal offset of about 500 feet and displacement of the north side to the west relative to the south side.

Normal Faults.—Evidence of normal faulting is commonly present where remnants of volcanic strata occur. Numerous faults are visible along the east flank of the Cerbat Range, most of which strike north-northwest in échelon, and the remainder of which strike northeast in échelon. The faults dip steeply, and displacement seems to have been dip-slip. One of the north-northwest striking faults has a probable length of more than 10 miles and a minimum vertical displacement of 700 feet.

A large normal fault occurs west of the Chloride district. It seems to be a boundary fault between the Sacramento Valley and the Cerbat Range and is here designated the Sacramento fault (Fig. 2). Vertical displacement on this fault and perhaps on allied faults that might be buried under an alluvial cover is believed to be responsible for the formation of the Cerbat Range, which is essentially an eastward-tilted block. On the basis of the assumed Tertiary age of the extrusive volcanic rocks, the faulting probably started in late Tertiary and possibly extended into Quaternary time. Even late Quaternary activity is suggested by eastward tilting and rejuvenation that has caused the development of Recent gravel terraces.

Relations Between Normal Faults and Vein Mineralization.—Both normal faulting and vein mineralization seem to have taken place after the conclusion of Tertiary volcanic activity. The question of their relative ages within the post-volcanic period immediately arises. If late rejuvenation along the west side of the range indicates boundary fault movement it is safe to say that normal faulting has been active after completion of sulfide mineralization. This is shown by veins that were truncated by erosion, buried under a blanket of alluvium, and later exposed by down-cutting that is a function of this rejuvenation.

There are no traces of mineralization along the Sacramento fault. It therefore might be assumed that the fault is post-mineral, especially as it passes within 2,500 feet of strong veins. But the assumption has little weight, as the amount of gouge that might form along a fault of this size could effectively seal it against hydrothermal solutions.

If mineralogical and textural differences could be demonstrated between veins at the base of the mountains and those several thousand feet higher, near the crest line, it might indicate that the mountains were elevated after vein formation was complete. If that were true the deeply eroded veins at the foot of the range should have features of greater depth of sulfide mineral formation. The veins, however, are the same from mountain top to pediment. Zoning does not seem to occur in these veins, and the opposing argument that the veins were formed after the sculpturing of the mountains also has no support.

The only conclusion is that sulfide mineralization was prior to or contemporaneous with the normal faulting.

VEIN DEPOSITS.

History and Production.

The first ore discoveries were made in 1863. Desultory production followed through the 1890's on near-surface oxidized ores that were mined for their gold and silver content. The period from 1906 to 1912 had the greatest sustained activity in the history of the region. Much development work was done below water level, and production was principally from sulfide ores. Since that time the main productive periods have coincided with base metal demand provided by the first World War and World War II.

Only two mines have large production records, the Golconda in the Cerbat district and the Tennessee-Schuylkill in the Chloride district. The Golconda

is credited with a gross production of $6,500,000 (12, p. 95) up to 1917. The mill was destroyed by fire in that year, and the property has not produced since. The mine was developed to a depth of 1,600 feet, and at one time it was the largest zinc producer in the state of Arizona. The Tennessee-Schuylkill produced a small amount of ore during the early nineties, operated steadily from 1910 to 1916, operated intermittently from 1917 to 1936, and produced more or less continuously from 1936 to 1949. It has been developed to a depth of 1,400 feet, has winzes to 1,600 feet, and has yielded about 300,000 tons of ore averaging 4.34 percent lead and 7.74 percent zinc and containing appreciable gold and silver (22, p. 4).

Hernon (23, p. 111) gives the following production figures for the Cerbat Range for the years prior to and including 1930:

Copper (lb)	Zinc (lb)	Lead (lb)	Gold	Silver	Total
2,900,000	95,587,344	55,350,000	$2,339,000	$5,038,000	$20,270,000

The total volume of ore from 1908 through 1933 was 615,514 tons, valued at $13,360,978 (12, p. 73). The production for the years 1934 to 1946 inclusive was 703,701 tons, with a total value of $9,508,187 (51). Considering the many years of early operation, from which no production statistics are available, the total value of ore gained from the Cerbat Range is probably close to $35,000,000.

An indication of the average grade of present ores is given by the milling records of 20,222 tons of custom ore that were treated by the Mineral Park Milling Co. from 1945 to 1947 inclusive. The average assay figures on this ore are 0.058 ounces gold, 3.56 ounces silver, 0.404 percent copper, 3.30 percent lead, and 5.67 percent zinc (32).

Distribution of Veins.

The general limits of the area within which sulfide-containing fissure veins occur are shown in Figure 3. It can be seen that the mineralization occupies an elongate zone or belt. This belt strikes approximately N 35 degrees W and is 4 to 5½ miles wide by 14 miles long. Centrally located within the belt is an area of "porphyry copper" mineralization. From south to north, in the Cerbat, Stockton Hill, and Mineral Park districts, and in the eastern portion of the Chloride district, most of the veins strike about northwest. This distributes the veins in échelon within the belt of mineralization. The prevailing trend is demonstrated in Figure 4, which is a point diagram prepared in the manner outlined by Billings (7). This technique, which utilizes the plotting methods of structural petrology, shows the poles of perpendiculars to surfaces such as folia, joints, and veins. Perpendicular surfaces are represented by points on the circumference of the plotting circle, and horizontal surfaces are represented by a point in the center.

The greatest concentration of veins occurs in the eastern part of the Chloride district, where more than 100 veins are present in an area of not more

than 6 square miles. The veins in this area follow the prevailing trend. In the balance of the Chloride district the veins deviate radically from this trend and strike in many directions. Figure 2 shows that the arrangement is not haphazard, however, but reflects an anticlinal pattern in the rocks. This is most obvious in veins that are parallel to the intrusive contacts of the Ithaca Peak porphyry sill.

Primary Minerals.

The following primary minerals have been identified in the vein deposits:

Gangue Minerals.—

Quartz	SiO_2—Most abundant; present in all veins.
Calcite	$CaCO_3$—Present in many veins.
Manganocalcite	$(Ca, Mn)CO_3$—De La Fontaine mine.
Siderite	$FeCO_3$—Minor, but widespread.
Fluorite	CaF_2—Chloride district; in 2 veins.

Ore Minerals.—

Pyrite	FeS_2	Common assemblage of mineral belt.
Marcasite (?)	FeS_2	
Arsenopyrite	$FeAsS$	
Sphalerite	ZnS	
Galena	PbS	
Chalcopyrite	$CuFeS_2$	
Tetrahedrite	$5Cu_2S \cdot 2(Cu, Fe)S \cdot 2Sb_2S_3$	Very rare.
Tennantite	$5Cu_2S \cdot 2(Cu, Fe)S \cdot 2As_2S_3$	
Proustite	$3Ag_2S \cdot As_2S_3$—Most abundant silver mineral; rare in present ores.	
Pyrargyrite	$3Ag_2S \cdot Sb_2S_3$	—Minor amounts, with proustite.
Polybasite	$9Ag_2S \cdot Sb_2S_3$	
Miargyrite	$Ag_2S \cdot Sb_2S_3$	
Gold	Au—Present in minor amounts in all ores.	

Bastin (3, p. 35) has recorded, also, the occurrence of pearceite ($9Ag_2S \cdot As_2S_3$), argentite (Ag_2S), and manganiferous siderite, $(Fe, Mn)CO_3$ as primary ore minerals.

Paragenesis of the Ores.

The following discussion is based on an examination of sixty-four polished sections. Most of the specimens were taken from mines, ore-bins, and dumps throughout the Chloride district. Others were taken at scattered locations in the balance of the mineralized belt. The results of the examination give a composite picture of the history of mineralization. The stages in this history that are found in any single mine or prospect have been dependent upon the local maintenance of fissures and openings and upon the variable physico-chemical conditions affecting the solutions. The paragenetic relations are summarized in Figure 5.

Age Criteria.—Prior to detailing the paragenetic relationships of the ore minerals, mention should be made of the criteria that were used in determining age diversity or similarity. Of the many criteria that have been suggested (5), only a few were felt to be sufficiently diagnostic to be relied upon. Depositional features in vugs and fractures, and cross-cutting veinlets, were used with confidence in determining successive deposition of minerals in any one section. Crustification banding was also used, with the realization in mind

that any single mineral layer might represent more than one stage of deposition. Such a condition is possible, as later replacement could add appreciably to an initial layer. Crystal outlines were used in places as indicative of mineral succession. As discussed by Bastin (4), this involves the assumption that where crystal boundaries of a grain are convex outward the grain is older than the surrounding mineral. Conversely, concave crystal boundaries out-

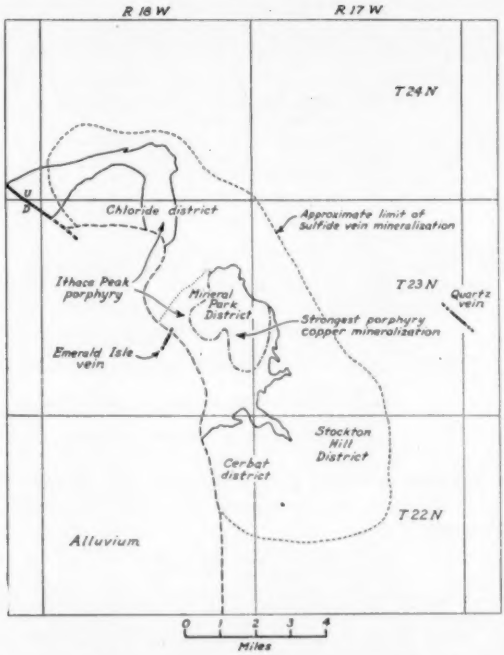


FIG. 3. Generalized diagram of distribution of mineralization in the Wallapai district. Note central location of porphyry copper mineralization and symmetrical pattern of superimposed fissure vein mineralization.

ward would indicate that the surrounding mineral is the older. This cannot be used haphazardly, however. Force of crystallization must always be considered; for example euhedral pyrite may develop either simultaneously with or later than surrounding quartz, and the application of this crystal outline principal would give an invalid result. It is most useful where supplemented by pitting, corrosion, or other replacement phenomena.

The only replacement features used with confidence were veinlets with non-matching walls, where attack on older minerals was reasonably clear. Supplementary evidence included "island to island" and "island to mainland" relationships. In this, isolated inclusions are assumed to be older than the

surrounding mineral where they show parallel orientation with each other and with a nearby parent mass. Of confirmatory value was the form of host-guest contacts, where boundaries smoothly concave toward one mineral may indicate that it is the guest. Care must be taken not to confuse this replacement "caries" type contact with crystal outlines, where concavity toward a mineral holds an opposite age connotation.

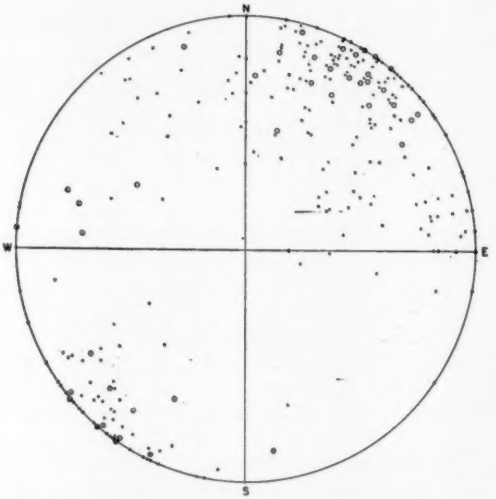


FIG. 4. Point diagram showing poles of perpendiculars to 268 veins in the Wallapai district. Plotted on upper hemisphere. Equal area projection. Dots represent veins in the Chloride district, small circles represent veins in the Mineral Park, Cerbat, and Stockton Hill districts.

It was virtually impossble to make direct determinations of simultaneous deposition. Perhaps the most reliable criterion is the occurrence of two or more minerals as adjacent segments of a veinlet filling, though this condition could also result from replacement. The lack of data showing age diversity might be taken to indicate simultaneity, but this is inherently weak. It is strengthened somewhat by the not uncommon appearance of features of successive deposition or replacement between two minerals, which, in another portion of the same polished section will display reversed relationships. This could mean that both minerals were available in the mineralizing solutions at the same time, providing separate stages are not indicated elsewhere.

As implied in the above use of the terms supplementary and confirmatory, no single criterion should be taken as diagnostic of a condition. Where several can be applied, however, the accuracy of determination is improved. By examining a large suite of polished sections, enough mutually supporting evidence should be found to give a consistent picture of paragenetic relations. The conditions displayed in any one polished section may be incomplete, but

through the study of many sections a composite history of mineralization can be compiled.

Introduction of Quartz.—Newly established fissures and re-opened old fracture systems were first occupied by quartz. Pressure conditions were apparently low enough so that self-sustained openings were maintained. As a result the rising solutions typically deposited euhedral crystals of clear to milky-white quartz. The formation of "comb crystals" lining the walls of open fissures was common. Quartz continued to be deposited intermittently throughout the period of vein formation.

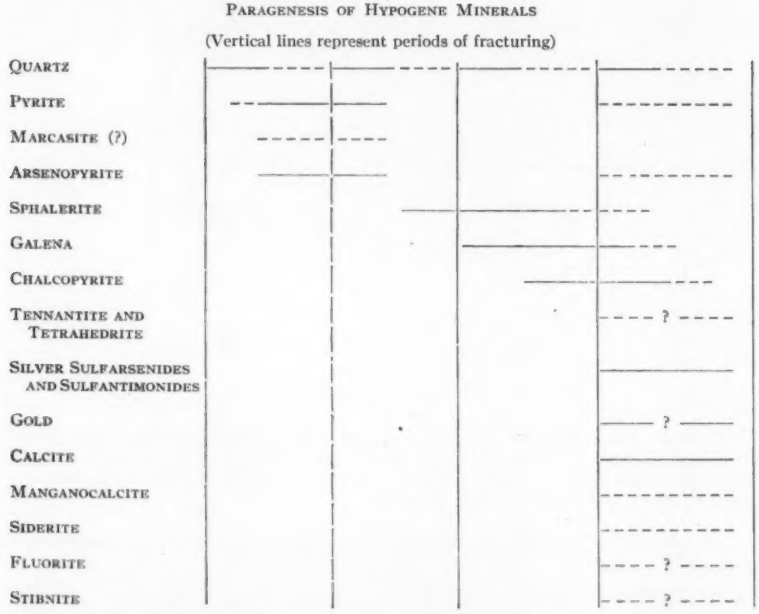


FIG. 5. Paragenesis of vein deposits. Horizontal spacing indicates relative positions of minerals, not time units. Dashed lines indicate minor significance.

Introduction of Pyrite and Arsenopyrite.—Pyrite and arsenopyrite were introduced after the first quartz began to be deposited. They typically developed crystal forms, and euhedral to subhedral intergrowths of early quartz, pyrite, and arsenopyrite are common. The evidence for the earlier time of introduction of the quartz is displayed in specimens where early quartz crystals, lining fissure walls, have been surrounded by pyrite and arsenopyrite, and the crystal faces of the quartz have been corroded and replaced.

No conclusive evidence was seen that would establish priority of introduction for either pyrite or arsenopyrite. One or both may occur in any single

specimen, though pyrite is more abundant regionally. Pyrite would be expected to form first, on the basis of the usual sequence of hypogene ore minerals (29, p. 122; 35). In many places pyrite is earlier and is replaced by arsenopyrite, but in other places the relations are reversed. The two minerals seem to be essentially contemporaneous. The bulk of the pyrite and arsenopyrite was deposited in this early stage, prior to the introduction of the rest of the minerals. Small amounts recur in later stages, however.

Marcasite (?).—In some specimens marcasite (?) and arsenopyrite occur as a very fine-grained mixture. Marcasite (?) was differentiated on the basis of its light yellow color and on polarization colors that differ from and are more vivid than those of arsenopyrite. The material seems to be contemporaneous with arsenopyrite.

First Intra-mineral Fracturing.—Mild and local fracturing that took place after the introduction of arsenopyrite and pyrite is present in a few specimens. It is shown by the presence of sphalerite as fracture fillings in the pyrite and arsenopyrite.

Introduction of Sphalerite.—After the major period of deposition of pyrite and arsenopyrite, zinc was added to the solutions, and sphalerite began to deposit. Its relative age is established by veining, and by its position surrounding crystals of early quartz, pyrite, and arsenopyrite. Most of the sphalerite is brownish black to grayish black but some is light brown. No distinction in relative ages can be made between these two types, and the variation can be explained best by the assumption of local differences in the nature of the zinc-containing solutions, notably in the amount of iron that was present.

Inclusions of chalcopyrite are abundant in the sphalerite. These vary from microscopic specks to blebs that can be seen with the naked eye. There is no uniformity in the orientation of the blebs. None of the chalcopyrite resembles a crystallographic intergrowth, though straight lines of inclusions, possibly formed along cleavage planes, are not uncommon. More often the inclusions are scattered at random or seem to outline invisible grain boundaries. Furthermore, chalcopyrite veins sphalerite, occurs outside of sphalerite, and also replaces it. According to the criteria listed by Schwartz (47) these features are not indicative of exsolution, and the presence of the chalcopyrite is therefore attributed to the effects of replacement along sub-microscopic openings in the sphalerite.

Second Intra-mineral Fracturing.—After the deposition of a considerable amount of sphalerite, many specimens show a second period of fracturing. Evidence of it is not abundant, but the fracturing is a little more widespread than was that of the first period. Veining by galena establishes its relative age.

Introduction of Galena.—In some specimens galena follows sphalerite in order of introduction, for galena veins, corrodes, and rounds crystals of early sphalerite. In many specimens, however, the two minerals seem to be contemporaneous. Reversals of paragenetic relations are common, and in bulk sphalerite and galena are best classed as "intermediate age" minerals. Both recur in small amounts associated with later minerals.

Third Intra-mineral Fracturing.—Some specimens display moderate fracturing that occurred after the deposition of both sphalerite and galena was largely complete. The fracturing is shown by cross-cutting veinlets occupied by later minerals and by brecciated vein material which has been cemented by late quartz.

Introduction of Chalcopyrite.—Blebs of chalcopyrite in sphalerite are interpreted as replacement features. Chalcopyrite also occurs as replacement grains along boundaries of sphalerite and galena and in veinlets cutting these and earlier minerals. Its time of introduction is believed to be later than the time of introduction of galena. This is based on the veining and replacement of galena by chalcopyrite and the lack of recognizable reverse relations. The chalcopyrite is present only in minor amounts and in small grains, however, and replacement features of chalcopyrite by galena might be present but not identifiable as such. Chalcopyrite occurs contemporaneously with all later minerals.

Introduction of Latest Minerals.—A varied assemblage of minerals was deposited during the last stage of mineralization. These minerals are minor in amount and, aside from gold, are lacking in the majority of specimens. Minor variations in the paragenetic relations of these minerals exist between specimens, but on the whole they seem to have been introduced at about the same time, after the bulk of sphalerite and galena had been deposited.

Tetrahedrite and Tennantite.—Tetrahedrite and tennantite are very rare and were only observed as microscopic grains. Tetrahedrite was seen in a specimen from the Mineral Park district and in a specimen from the Optimo mine. What may be tennantite occurs in a specimen from the Lucky Baldwin prospect. The two minerals are contemporaneous with silver minerals in tiny veinlets and cavity fillings.

Complex Silver Minerals.—The most abundant silver mineral is proustite, and it was observed in only a few specimens. Accompanying it in some specimens are minor amounts of pyrargyrite, polybasite, or miargyrite. The relative age of these minerals is established by their presence in veinlets cutting across galena and chalcopyrite.

These complex sulfides are believed to be primary. The best evidence of this is that quartz, galena, chalcopyrite, and ruby silver occur as segments filling the same veinlet. This is indicative of simultaneous deposition, and if the galena and chalcopyrite are primary the ruby silver must be primary. Bastin's (3) detailed study in 1913, a time when specimens of the silver sulfides were more abundant, gives many other criteria which also suggest that the silver sulfides are primary.

Gold.—Gold, which invariably is recovered in small amounts from the primary ores, has not been detected in hand specimens nor under the microscope, and its paragenetic position is unknown.

Calcite.—Calcite is the most abundant of the late minerals. It is present in many veins and in some places constitutes a large part of the gangue. Calcite is commonly present in specimens that show the late period of intramineral fracturing, and it fills veinlets that transgress galena and sphalerite.

The calcite, which is milky-white to colorless, is common as crusts of euhedral crystals.

Manganocalcite.—White to pale pink manganocalcite forms the gangue of a specimen from the De La Fontaine mine. The refractive indices were determined as $N_e = 1.534$ and $N_o = 1.7$ plus, which indicates a content of approximately 42 percent $MnCO_3$ (27). It veins galena in several places and is possibly the same age as calcite.

Siderite.—Siderite was observed in only a few specimens but from such widely scattered locations as the New London mine, in the Cerbat district, and the Lucky Baldwin prospect, in the Chloride district. It was probably introduced at the same time as calcite for it veins galena and sphalerite. It ranges from light brown to grayish black in color.

Fluorite.—Fluorite occurs in at least two veins. Specimens collected from the dump of the Altata mine contain small clusters of colorless to light gray cubic crystals one-sixteenth inch or less in size. These crystals are set in a matrix of black oxide material, and none is in contact with the hypogene sulfides. In a specimen from the Tintic mine a small band of colorless fluorite is superimposed upon a layer of quartz. This fluorite likewise does not occur in contact with any sulfides, and its paragenetic position cannot be determined.

Stibnite.—Stibnite occurs in the Chloride district, but no economic amounts have been discovered. The known deposits consist of a few small pockets located within a granite porphyry dike. This dike is exposed about 600 yards northeast of the Hercules mine and runs parallel with the Badger-Hercules veins in a west-northwest direction. A distinct vein is lacking, but the prospect holes have a linear disposition along the length of the dike, and the granite porphyry is hydrothermally altered.

Examination under the microscope reveals that the granite porphyry was subjected to mild fracturing that established small openings. These were utilized by mineralizing solutions which first deposited quartz, typically in small euhedral crystals. Stibnite followed, and it surrounds and corrodes small comb quartz crystals. Later quartz occurs in veinlets cutting the stibnite. No other sulfides were observed in the deposits, which prevents any satisfactory dating or placing of the stibnite in the regional paragenesis. There is the possibility, of course, that the stibnite represents a different period of mineralization.

Post-mineral Fracturing.—In many specimens post-mineral movement is evident and in some places thorough brecciation has been accomplished. The lack of any primary mineral filling in the fractures indicates the post-mineral age. The effects are well demonstrated in specimens from the Payroll mine dump. In these complete brecciation took place, resulting in angular fragments averaging less than half an inch in size, which have been tightly cemented by iron oxide.

Summary.—Emphasis has been placed on the time of introduction of the various minerals, for regionally the sequence is uniform. Generalizations regarding the period of deposition of any particular mineral, however, cannot be made easily. Perhaps the best summary statement is that quartz was deposited intermittently through the period of mineralization, the bulk of the

pyrite and arsenopyrite preceded sphalerite and galena, and the bulk of the latter two minerals preceded the latest minerals. Deposition at any particular time and place was a function of such variable factors as temperature, pressure, concentration, rate of solution ascent and permeable openings. As a result, the mineral relations in some specimens differ from those in others, but all are contained within this general paragenetic pattern.

General Features of Oxidation.

Supergene Minerals.—The following minerals have been determined from the oxide zone of the vein deposits:

"Limonite"	Fine-grained isotropic oxides of iron; very abundant.	
Goethite	$Fe_2O_3 \cdot H_2O$	Present in limonite.
Jarosite	$K_2O \cdot 3Fe_2O_3 \cdot 4SO_3 \cdot 6H_2O$	
Plumbojarosite	$PbO \cdot 3Fe_2O_3 \cdot 4SO_3 \cdot 6H_2O$	
Limonitic jasper	———	Common
Hematite	Fe_2O_3	Accompanies limonite in places.
Chalcanthite	$CuSO_4 \cdot 5H_2O$	Mine walls.
Iron-copper chalcanthite	$(Fe, Cu)SO_4 \cdot 5H_2O$	
Anglesite	$PbSO_4$	Common.
Cerussite	$PbCO_3$	
Covellite	CuS	
Scorodite	$FeAsO_4 \cdot 2H_2O$	
Mimetite	$Pb_5ClAs_3O_{12}$	
Chalcocite	Cu_2S	Rare.
Cuprite	Cu_2O	
Native copper	Cu	
Malachite	$2CuO \cdot CO_2 \cdot H_2O$	
Azurite	$3CuO \cdot CO_2 \cdot H_2O$	
Zinc carbonates		
Native silver	Ag	
Ferrous arsenate (?)		Coatings.
Manganese oxides		
Gypsum	$CaSO_4 \cdot 2H_2O$	Rare.
Calcite	$CaCO_3$	

Bastin (3, p. 35) mentions secondary argentite (Ag_2S) and proustite ($3Ag_2S \cdot As_2S_3$) as being very minor constituents of some ores, and Schrader (45, p. 49) states that horn silver (cerargyrite, AgCl) was an important mineral in the oxide zone of many veins.

Oxidation effects have been of considerable economic importance. Rich deposits of native and horn silver were formed in the oxide zones of many of the veins, and it was the discovery and exploitation of these near-surface deposits that was responsible for the early prosperity and growth of the region. Most of these deposits were exhausted prior to 1900, but oxide deposits of marginal grade received attention in the years immediately preceding World War II.

As might be expected in an arid climate where relatively high temperatures prevail, and where the irregular surface flooding is widely spaced in time, oxidation has been thorough in the upper portions of the veins. The effects extend as deep as 350 feet in veins on the higher slopes where the water table is consistently low. However, the general limit of strong oxidation is about 100 feet, and in most veins the depth is between 50 and 80 feet. The transi-

tion from oxides to sulfides commonly takes place within a distance of 10 to 15 feet.

The products of oxidation, being derived from an aggregate of sulfide minerals, are numerous. Furthermore, differences from place to place in occurrence and quantity of the sulfide and gangue minerals add to the complication of the end products. However, diagnostic oxide minerals, textures, and structures occur in many veins. These aid in the reconstruction of processes of solution and deposition within the superficial zone and can be of value in the search for new ore bodies.

Role of Gangue.—Locke (30) has classified gangues as inert, and slowly, moderately, or rapidly reacting. The predominance of quartz as a primary gangue mineral in these deposits might be expected to give an inert environment for oxidation processes.. In some places in the veins this seems to have been true. In other places, where calcite was abundant, rapid neutralization occurred. As a general rule, though, the feldspathic nature of the wall rocks and the abundance of altered country rock and clay gouge within the veins has provided what Boswell and Blanchard (9) term an environment of moderately slow neutralizer.

Limonite.—In the following discussion of the products derived from the various primary minerals the term "limonite" will be used broadly. In all specimens that were examined microscopically the bulk of the iron oxides is microcrystalline, isotropic, and indeterminable as other than "limonite." Of widespread occurrence, however, are small amounts of goethite and jarosite. In some specimens hematite and plumbojarosite were observed, the latter in association with other lead minerals. The probable presence of some or all these minerals will be implied where limonite is mentioned.

Pyrite.—Pyrite is present in all the veins. This mineral, through reaction with oxygenated water, produces the powerful solvents ferric sulfate and sulfuric acid, which, as Bateman (6) states, are effective agents in the oxidation of sulfide minerals. Pyrite has been the chief source of the ubiquitous limonite, both by the direct production of ferric hydroxide and by reactions of ferric sulfate with the other sulfide minerals.

Arsenopyrite.—The typical oxidized derivative of arsenopyrite is a granular intergrowth of scorodite and limonitic particles in a distinctive arborescent structure (8). If the arsenopyrite was part of a complex sulfide mixture the granular intergrowth is modified by the presence of a cellular boxwork structure, a granular fretwork in the matrix, and the presence of intergrown extraneous minerals, notably mimetite. In oxide specimens collected from the vein deposits of the Wallapai district pale green to olive-drab granular and arborescent encrustations of scorodite coat the walls of oxidation voids. Limonite accompanies the scorodite but is not abundant. Cellular boxworks and granular fretworks do not seem to occur, but this may be an accident of collection. The association of extraneous minerals is well shown in a specimen from the Mollie Gibson mine, where numerous colorless to white tiny prismatic crystals of mimetite are intergrown with the scorodite.

Further evidence of the possible former presence of arsenopyrite is the occurrence in oxide specimens of apple-green stains. These are associated

with the derivatives of sphalerite and galena and are presumably ferrous arsenate (9, p. 441).

Sphalerite.—Zinc sulfide reacts readily with oxidizing solutions to produce zinc sulfate. The latter has a relatively high solubility and tends to be carried away by downward percolating waters. In the completely oxidized ores this process has been very effective for no traces of zinc minerals remain. In partly oxidized ores secondary products after sphalerite are present in small amounts. Small cracks in some sphalerite will effervesce with hydrochloric acid, indicating the possible presence of films of smithsonite, and sphalerite that has come in contact with cupric sulfate solutions has developed irregular veinlets and borders of covellite.

Zinc has been lost, but its former presence can be demonstrated. The ore deposits are characterized by an environment of moderately slow neutralizer, and under such a condition sphalerite tends to change into distinctive residual structures of limonite and limonitic jasper. Examples of coarse cellular boxworks, fine cellular boxworks, and cellular sponges correspond with the three types described by Boswell and Blanchard (9, pp. 424–431). The agreement is not surprising in view of the fact that these authors used two specimens from the Golconda mine of the Cerbat district in figures illustrating the typical development of coarse cellular boxwork.

Galena.—In contrast to the loss of zinc, lead is well preserved in the oxide zone. This is to be expected, as lead sulfide, reacting with oxidizing solutions, forms the highly insoluble mineral anglesite. Coatings of anglesite are common on partly oxidized galena, and kernels of such protected galena can be seen even at the surface of veins. Most of the anglesite has reacted with water containing carbon dioxide, and the anglesite has a coating of cerussite. In some specimens the reaction has been complete, and cerussite is the only lead mineral present. Cerussite is also relatively insoluble and is abundant in the oxide zone. Like sphalerite, some galena has reacted with cupric sulfate solutions to form veinlets and rims of covellite.

Though the former presence of galena is readily detected from the occurrence of the insoluble sulfate and carbonate, it is also indicated by the development of residual structures of limonite and silica. Boswell and Blanchard (9, pp. 431–438) describe cleavage boxworks, partially sintered crusts, ragged cellular structure, and an ochreous orange limonite color as diagnostic derivatives. Cleavage boxworks are well developed, and their fine, closely-spaced, parallel cell walls are easily identified. The other features may be present in these veins but are difficult to distinguish with any degree of assurance.

Chalcopyrite.—Chalcopyrite is present only in minor amounts in the sulfide ores and therefore has not contributed significant quantities of material to the oxide zone. But where formed the oxide products are of considerable variety. In the presence of acid solutions chalcopyrite is easily converted to copper sulfate. Hydrated forms of this, as chalcanthite and iron-copper chalcanthite, can be observed along the walls of drifts in many of the mines. The basic carbonates of copper, malachite and azurite, are abundant in the Clyde vein, and malachite occurs in small amounts in a few other veins. These minerals probably formed through reaction of copper sulfate with carbonate

gangue material. Secondary chalcocite also occurs in the oxide zone of the Clyde mine, where the necessary neutral conditions for its formation seem to be due to the presence of carbonate gangue. In places oxidation of the chalcocite has produced cuprite. Continued action, possibly from the effect of ferrous sulfate, has resulted in the reduction of the cuprite to native copper. Cuprite and native copper were observed only in the Clyde mine, which has an unusual amount of chalcopyrite in the primary ore, and their development represents a special and not a general condition.

Covellite has developed through the action of cupric sulfate on sphalerite and galena. Minor amounts of covellite have formed in similar fashion from blebs and small veinlets of chalcopyrite that exist in partly oxidized specimens.

Due to the fine grain size and small quantity of chalcopyrite in the primary ores, characteristic limonite structures would not be expected and have not been observed in the oxide specimens.

Silver Minerals.—The complex silver minerals were present in quantity in the upper portions of some of the veins. These minerals would react easily with oxidizing solutions to form silver sulfate. Bastin (3, p. 18) determined a chlorine content of 80 parts per milion in a water sample from Tennessee Wash. With such surface waters the silver sulfate should react to form cerargyrite. Some argentite would be expected where the reactions were not complete. Part of the silver sulfate in the middle and lower portions of the oxide zone should suffer reduction, resulting in the production of native silver. This order is borne out in the history of the mines, for horn silver was the chief near-surface ore mineral, and plates and wires of native silver were encountered at greater depth.

Gold.—Small quantities of gold have heightened the value of many oxide ores through concentration resulting from the leaching away of sulfide minerals. In addition, some enrichment may have occurred through weathering and the mechanical downward shift of gold particles. Chemical enrichment is thought to have been negligible.

Other Minerals in the Oxide Zone.—Small seams of selenite were observed along the footwall of the Silver Hill vein. These seams probably formed by the reaction of gangue calcite with sulfate solutions. Small white stalactites of calcite are currently forming on the back of the main adit in the Mint mine. The calcite has a rough, mammillary outer surface and a finely crystalline interior. Black coatings, which appear to be manganese oxide, are common on the surface specimens of vein material.

Interpretation of Gossans.—Various features of oxidation could be used to advantage in detailed examination and prospecting of the veins. Stoped sections of veins often extend to the present surface, and some of these must have followed economic ore bodies. A few are reported to have lain beneath depressions along the strike of the veins. Prospecting for depressions that have resulted from the oxidation shrinkage of sulfide ore bodies might prove worthwhile. The method is complicated, however, by the fact that many veins contain large quantities of soft gouge that erodes easily and produces similar effects.

Lead minerals are persistent in the oxide zone, and in places kernels of galena occur at the surface. That they may have been overlooked despite the long history of prospecting and mining in the region is emphasized by the fact that indications of this type led to the discovery of a small but relatively high grade deposit in the Mineral Park district in the summer of 1947.

Less obvious, but perhaps of equal value, are the diagnostic boxworks and limonite residues left in the gossans by sphalerite and galena. Systematic and detailed search for these derivatives could be of considerable value in guiding exploration. It should be pointed out, though, that the absence of diagnostic derivatives in an outcrop might not mean a lack of sulfides at depth, as the residues may be mutually interfering or may be masked by derivatives of pyrite. If the pyrite content is greater than one-quarter of the total volume of the mixed sulfides the diagnostic derivatives will fail to develop (9, p. 441). This ratio undoubtedly is exceeded in places in these ores.

Secondary Enrichment.

Secondary enrichment has not been important in the vein deposits. Zinc was removed from the oxide zone but was not precipitated at depth. Lead was oxidized, but the products remained at or near the site of the original sulfides. The same seems to have been true of the silver minerals, inasmuch as high-grade silver ore came from the oxide zone. Furthermore, the silver sulfarsenides and sulfantimonides are believed to be primary. Thus, there has been little impoverishment in the oxide zone that could lead to enrichment below the water table.

Cupric sulfate solutions, however, derived in small quantity from chalcopyrite, in places have penetrated the primary mineral zone. The result has been the rare development of insignificant quantitites of chalcocite after pyrite, and covellite and chalcocite after chalcopyrite. More common has been the formation of films of covellite on sphalerite and galena. Technically this amounts to copper enrichment, but it has not added to the value of the ore.

Wall Rock Alteration.

Effects of wall rock alteration that are visible in the field ordinarily extend only a few feet from the veins. The most obvious alteration occurs in the numerous mafic dikes that occupy one or both walls of many veins. However, deuteric alteration is a common feature of such dikes, especially lamprophyres, and hydrothermal action cannot be assumed to be the sole agent. Furthermore, the available portions of many of the veins are solely within the oxide zone, and in the walls of these veins alteration effects are partly due to supergene processes.

Comprehensive investigation of the alteration has not been attempted, but a series of samples collected underground in the Tennessee-Schuylkill mine has given an indication of the type and degree of change imposed on granite gneiss, the prevailing rock type of the mineralized area. Samples were taken along the cross-cut at the 1,000 foot level from the shaft to the vein. The vein is approximately five feet wide where intercepted by the cross-cut. The

back is timbered, but on the west wall, where sampling was started, 12 inches of white quartz containing narrow seams of sulfide minerals is visible.

The last sample taken was 150 feet west of the Tennessee vein. However, a parallel veinlet occurs 50 feet west of the vein, and the effective distance for solutions to travel to this specimen is only 100 feet. The rock is a fine-grained injection gneiss composed of quartz, feldspar, pyroxene, and biotite. Selective alteration has affected about 25 percent of the minerals, whereas the rest are clear and fresh. Part of the alteration may be deuteric, but the presence of abundant pyrite, which is not a normal component of the gneiss, indicates that mineralizing solutions have penetrated the rock. Secondary products are biotite, formed along the course of a veinlet of pyrite and chlorite; chlorite, muscovite, and biotite, after diopside; chlorite, epidote, and magnetite after primary biotite; and sericite, chlorite, epidote, zoisite, and clay mineral in microcrystalline aggregates after feldspar. A well formed vermicular crystal 0.13 by 0.06 millimeter in size suggests that the clay mineral is kaolinite.

With the exception of the occurrence of calcite, formed in some specimens after biotite and feldspar, this suite of secondary minerals characterizes the country rock to within a short distance of the vein. Alteration does not seem to have affected more than 25 percent of the minerals, and in some specimens not more than 10 percent. The first change in the alteration suite was noted in a specimen taken 30 feet west of the vein. The occurrence of a parallel veinlet 20 feet west of the vein means a distance of 10 feet from a mineralizing channel. This specimen is a fine-grained garnetiferous granite gneiss about one-quarter selectively altered to chlorite, calcite, epidote, pyrite, sericite, clay mineral, sphene, and possibly biotite. It is similar to specimens taken farther out, except that secondary sphene occurs as replacement lenses in biotite.

A specimen taken 10 feet from the main vein is completely altered and comparable in every respect to rock immediately adjacent to the vein. The alteration is anomalous, though, and must have been caused by a solution channel not visible on the wall of the cross-cut. The probable presence of such a channel is supported by the occurrence of veinlets of clay mineral in the specimen.

A specimen of garnetiferous granite gneiss taken five feet from the vein is only 10 to 15 percent altered. The secondary minerals are chlorite, epidote, pyrite, biotite, sericite, and clay mineral. Sphene is present but does not seem to be secondary, though it was expected on the basis of the occurrence of secondary sphene in the specimen taken 30 feet from the vein.

Next to the vein and in a zone not more than two feet wide the rock is thoroughly altered. A fine-grained gneissic texture is visible, but unless some primary quartz is present no original minerals have survived. Bleaching is prominent, and the rock is colored light gray to white. Irregular, interlocking grains of quartz make up 35 to 40 percent of a specimen that was cut next to the vein. Apparently contemporaneous with the quartz is approximately 3 percent of white mica, scattered through the section as tiny plates. A few subhedral crystals of pyrite are earlier than the quartz and white mica, or contemporaneous, for the pyrite is corroded by the latest minerals. The latest minerals are sphene, sericite, and clay mineral. The sphene makes up approximately 5 percent and the sericite and clay 55 percent of the rock.

Most of the sphene occurs as long stringers and lenses replacing the plates of white mica. It follows the foliate structure of the mica with remarkable regularity in most places. The balance of the sphene occurs as irregular grains and tiny crystals associated with the sericite and clay mineral. In the specimen taken 10 feet from the main vein the sphene is intergrown with sericite in a comb crust that lines the walls of a microscopic clay mineral veinlet. The sericite and clay mineral in this thoroughly altered rock are about equal in amount and are present in microscopic intergrowths. Each was observed to cut the other in microscopic veinlets, and the assumption is that the sericite and clay mineral are essentially contemporaneous in age. They both corrode and replace the quartz and white mica.

On the basis of the foregoing observations, the alteration processes can be divided into three stages:

(1) First is the widespread but weak development of chlorite, pyrite, epidote, sericite, clay mineral, and minor amounts of biotite and calcite. This aptly can be termed propylitization, for it is similar to the stage of propylitic alteration that characterizes many mining districts (46; 29, pp. 457–458).

(2) Second, and restricted to a narrow zone adjoining the vein, is a stage of silicification accompanied by the development of flakes of white mica. Pyrite may or may not be contemporaneous with this stage. A transitional zone with the preceding propylitic minerals probably exists, but in the specimens that were examined the earlier alteration products, possibly excepting pyrite, have been destroyed.

(3) The last and presumably most intense stage is distinguished by the formation of sericite, clay mineral, and a small quantity of sphene. These minerals replace the quartz and white mica, and in extreme alteration sericite, clay mineral, and sphene should be the only minerals present.

That the ultimate stage is represented principally by sericite and clay mineral is shown by totally altered specimens of diabase, granite porphyry, and hornblende schist that were taken from the walls of three different veins. Aside from a few residual quartz grains in the granite porphyry, relict textures are the only remains of the original rocks. The specimens are yellowish gray, consist of about equal amounts of sericite and clay mineral, and are stained to varying degrees by limonite. The specimens came from the oxide zone, and pyrite or sphene, if originally present, could easily have been removed. Furthermore, some of the clay mineral could be of supergene origin. The bulk of the clay mineral, however, is believed to be hypogene, on the basis of the clay mineral that occurs in the wall rocks 1,000 feet below the surface of the Tennessee vein. The formation of the same final alteration products, regardless of the initial type of wall rock, shows a strong dependence on the composition of the solutions and not on the composition of the wall rock. As discussed by Butler (10), this is an expected feature of hydrothermal alteration.

Excellent specimens of clay mineral were collected in the roof of the south stope at the 1,000 foot level of the Tennessee-Schuylkill mine in June 1948. The mineral occurred within an area of sulfide minerals and in association with late quartz and crustified calcite veinlets that cut earlier quartz and sul-

fides. The clay mineral is an open space filling, and in one specimen it is situated between veinlets of quartz and calcite. The clay mineral contains tiny pyrite crystals and irregular grains of sphalerite, and in hand specimen it has a distinct pearly luster. Under the microscope it resolves into a microcrystalline aggregate of grains that have an average diameter of 0.02 millimeter and extremely low birefringence. Immersion oil determinations gave a refractive index of 1.562, with another index that seemed to be about 1.558. On the basis of the refractive indices, the pearly luster, and the nature of occurrence, the mineral is tentatively identified as nacrite. The limited data correspond well with the descriptions given by Ross and Kerr (40) for this mineral. Though its source is unknown, its hydrothermal nature seems indisputable.

Successive stages and zones of wall rock alteration have been recognized in many mining districts. Features similar to those that have been described above occur at Cerro de Pasco. In that locality Graton and Bowditch (19) recognize a feeble phase, characterized by chlorite, calcite, and epidote; a moderate phase, marked by sericite, pyrite, and quartz; and an intense phase, in which the rock is converted to quartz, pyrite, kaolin (dickite), and alunite. Residual sericite is common in this last phase. The mineralogy is similar to that in the altered wall rock of the Tennessee vein, and the high-temperature dickite is noteworthy as it is supposed to represent a late acid condition in the mineralizing solutions (44). Sales and Meyers (43) also mention dickite as occurring near the hot center of the Butte, Montana camp and in association with sericite. This seems analogous to the sericite and nacrite (?) associated with the Tennessee vein.

The introduction of sphene in the last and most intense stage of alteration is unusual. Sphene is not uncommon, however, as a deuteric alteration product in igneous rocks and is present in many contact metamorphic rocks. Gillson discussed such occurrences in a paper on the Pend Oreille district (17). The pneumatolytic or hydrothermal origin of sphene in igneous and metamorphic rocks indicates that its association with hydrothermal vein formation might be expected. Recent analyses by Sahama (41) show that the sphene lattice, of the specimens examined, contains fluorine in remarkable amounts. Jaffe (26) has also demonstrated the presence of fluorine in a number of specimens of sphene. This is perhaps significant as to the mode of origin of sphene. It would be interesting to know if any correlation exists between the amount of contained fluorine and a deuteric or hydrothermal source.

Vein Structure and Expression.

The veins are well-defined tabular bodies. Gouge and breccia line most of the walls, and the walls break freely from the country rock. Frozen walls, cemented by primary quartz deposition, are less frequent but not rare. The fractures occupied by the veins are regular and in large scale are straight or broadly curving. In detail, changes in strike and dip are numerous but are not pronounced. Splits and "horsetails" occur in places in conjunction with small changes in vein orientation, and linkage of veins along the strike is com-

mon (Fig. 2). In the eastern part of the Chloride district, where most of the veins have a northwest strike, dips in the upper portions of some veins are opposed to those in other veins. The dips are steep, and exploration has not gone deep enough to disclose possible intersections.

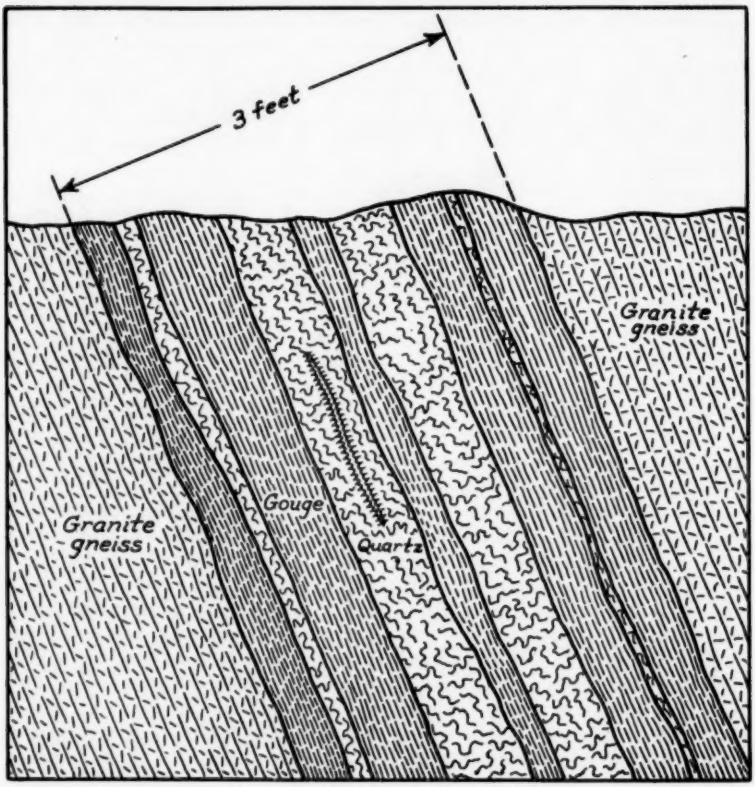


FIG. 6. Cross section of Alice vein showing laminated structure formed by alternating layers of quartz and gouge.

A common feature in the veins is a laminated structure formed by alternating layers of gouge and quartz. The quartz is typically vuggy and may or may not contain sulfides. As an example, a vein may have four or five layers of quartz that are 1 to 6 inches thick, separated by layers of gouge of similar thickness. The structure is illustrated in the sketch of Figure 6. Much of the gouge contains crushed and rolled fragments of country rock and quartz.

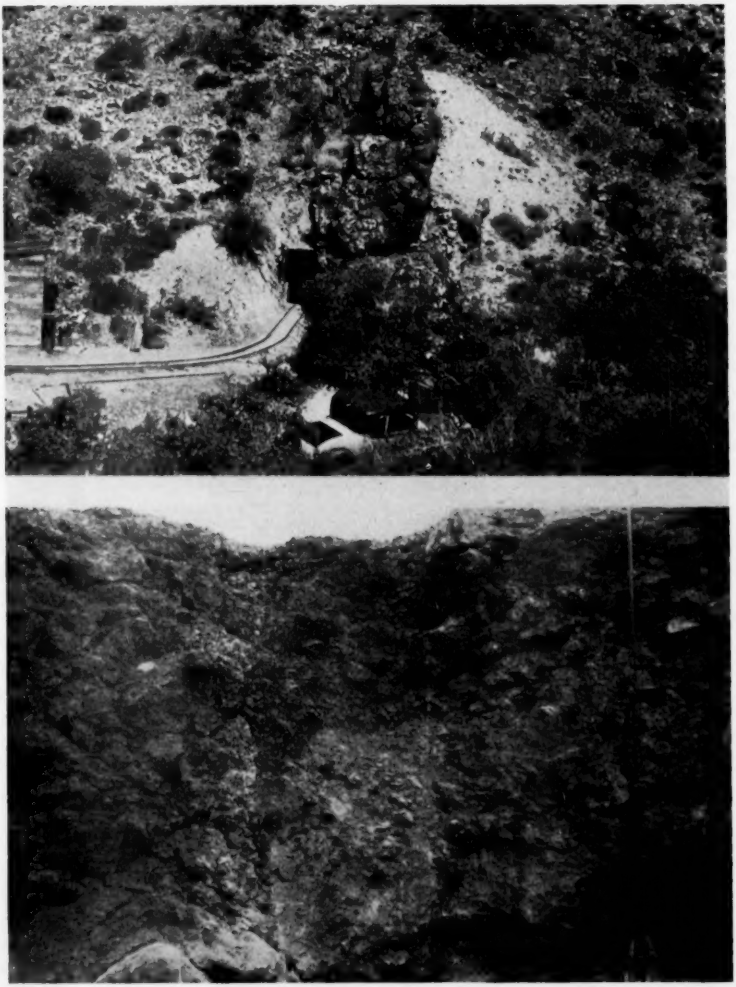


FIG. 7. (Upper) Outcrop of Mary Bell vein. Prominent quartz ledge stands as much as 10 feet above surrounding country. View looking north.

FIG. 8. (Lower) Exposure of Emerald Isle vein in the west end of the open pit, Summer 1947. View looking south.

Most of the veins are only a few feet wide. Widths up to 80 feet occur, but wide veins more accurately can be called mineralized zones, for they have a composite structure in which a number of closely-spaced narrow veins are separated by gouge and country rock that has been altered, sheared, crushed, and in places silicified. Considerable variations in thickness occur, and portions of some veins have no surface trace. In such places indications of mineralization, in the form of small quartz stringers or altered country rock, are commonly present in prospect holes along the line of strike. Most of the veins are continuous and distinct at the surface. Many extend for over a mile, and the Tennessee vein can be traced two and one-half miles.

The surface expression of the veins is diverse. Where a wide composite vein zone occurs the combination of iron-stained quartz and altered schist and gneiss gives a reddish brown to purplish brown outcrop, flush with the adjacent surface in most places. In some narrow veins strong quartz ledges protrude several feet above the general surface. The quartz in these ledges is stained yellowish to reddish brown and black, and some is honeycombed from the removal of primary sulfides. Ledges of this type occur along the Mary Bell and North Georgia veins, and outcrops of fairly solid quartz stand as much as 12 feet wide and 10 feet high (Fig. 7).

General Features of Primary Deposition.

Certain aspects of deposition are common to all the veins. One of the most obvious features is an abundance of comb and rosette quartz and associated open vugs and druses. Euhedral crystals of quartz one-half to three-quarters of an inch in diameter are not unusual. Sulfide minerals are associated with many of the combs. In addition to open combs, crustification structures formed by successive layers of minerals are also abundant. Many of the quartz seams that are part of the laminated vein structures consist of these crustified fillings. A line of small vugs characteristically marks the center-line of a filling. An example of symmetrical filling of a small fissure within a vein is shown in Figure 9. These features imply that open space filling was an important factor in the formation of the veins. Replacement of hypogene minerals by one another operated to a large extent, and replacement of the wall rocks was widespread but chiefly by quartz, pyrite, sericite, and kaolin. The vein boundaries are sharp, and the ore minerals seem to have been deposited entirely within the fissures.

Variable crystallinity is another characteristic feature, especially in the quartz. In some places the sulfide minerals range from microscopic grains to crystals more than 3 centimeters in size, but in most specimens the range is from a few millimeters to 1 or 2 centimeters. In quartz, however, it is not uncommon to find a chalcedonic variety immediately adjacent to euhedral crystals. Layers of cryptocrystalline quartz occur in crustified bands and usually have a delicate scalloped banding that is suggestive of rapid deposition (18, p. 189). In some specimens fragments of early quartz and country rock have been surrounded by successive delicate layers of cryptocrystalline and finely crystalline quartz, producing a cockade structure (29, p. 170) (Fig. 10).

FIG. 9. (Upper) Small fissure filling from New Moon mine, south face of drift, 150-foot level, Summer 1948.

FIG. 10. (Lower) Cockade structure in delicately banded chalcedonic and fine-grained quartz from Aurora vein.

No evidence was found of distinct zoning, either vertical or horizontal within the veins. On the contrary, changes in texture or structure follow no consistent pattern, and all the data that were collected on the mineralogy and the percentages of various metals indicate a uniform mineral distribution. Veins on the edges of the mineralized belt contain the same minerals, in the same average proportions, as those in the center. The ore in the bottom of the Tennessee-Schuylkill mine is essentially the same as that found in veins near the crest of the range, though in places this means a vertical difference of over 3,000 feet. That vertical zoning of the precious metals must have obtained is suggested by the reportedly rich values mined from the oxide zone, for present ores do not seem capable of providing extreme values, even through complete leaching and alteration of the sulfides. If this were true, however, the veins at high elevations should still contain better values than those at low elevations, and such is not the case. Rather, two veins that have produced ruby silver in quantity in the last 20 years, the Diana (Arizona Magma), of the Chloride district, and the Keystone, of the Mineral Park district, are both at low elevations. The distribution of rich silver sulfides appears erratic and was probably controlled by the localized coincidence of permeable openings with a period of high silver concentration in the mineralizing solutions.

According to Garrett (16), local horizontal zoning occurred in some of the ore shoots in the Tennessee-Schuylkill mine. Variations in other veins also have been reported, and portions or all of some ore shoots are said to have been characterized by high gold, or lead, or zinc. Again, these variations may have been dependent on the openings that were available at any one time to changing mineral solutions.

A zonal arrangement is present in the distribution of the vein fissures, as they occur in a long belt, at the center of which is the "porphyry copper" mineralization of the Mineral Park district (Fig. 3). A case might be made for metal zoning on the basis of the cupriferous area surrounded by lead-zinc deposits. But the lead and zinc also occur within the "copper zone" and are separated by a break in time of mineralization. The factors of time and structure have been paramount in determining the zonal relations of these two periods of mineralization.

Ore Shoots.

Despite the abundance of veins, comparatively large quantities of ore have been found only in the Tennessee-Schuylkill and Golconda mines. In the Tennessee-Schuylkill the ore shoots range from 1 to 15 feet in width, from 100 to 500 feet in strike length, and from a few hundred to more than 1,000 feet in depth. The width of ore in most veins is from 1 to 5 feet, and the length and depth vary from as little as 10 feet to as much as 350 feet.

The lack of ore shoots of appreciable size may be due in many places to the quantity of gouge filling in the veins. Sales (42) has stated that "A gouge filled fissure appears to be distinctly unfavorable to ore deposition, probably in part because the gouge chokes the fissure and prevents the access of mineral bearing solutions, and in part because the movement along such a fissure is so nearly continuous as to give no chance for the deliberate and undisturbed

chemical action which seems requisite for the formation of large, clean bodies of ore." Large, clean bodies of ore certainly have not been encountered in the exploration of most of these veins. Rather, the typical occurrence of ore is in discontinuous layers and lenses, which are situated on the hanging wall, foot wall, or within the central portion of a vein. The ore in many veins is surrounded by gouge that needs support during mining to prevent dilution of the ore. Much of this gouge, which has resulted from attrition by fault movement and hydrothermal kaolinization and sericitization of the country rock, was formed prior to the depositon of the sulfide minerals. This early presence of impermeable material, at least locally choking the fissures, has apparently prevented the deposition of any large amounts of ore in many of the veins. The dominance of gouge, however, is not universal. Some veins are predominantly quartzose and have tightly frozen walls.

Segregations of ore seem to have formed where open spaces were available for direct deposition of the valuable minerals. Even in heavy gouge, bands and lenses of primary minerals display comb structures, vugs, and crustification that could only form in cavities. There is no obvious wall rock control in the location of ore, and fillings are as wide in one rock as another. The veins may pinch and swell, but there is no distinct correlation with any rock type. If the fissures passed into volcanics or sediments radical changes might be expected (33; 29, pp. 198–199). As it is, the high-grade metamorphic and intrusive igneous terrane, despite its petrologic variety, has acted as a uniform host for fracturing.

In view of the displacements indicated by the striations and slickensides in the veins, most of the open spaces favorable for ore shoots were probably a function of changes in the configuration of the fissures. Garrett (16, p. 110) states that "ore shoots in the Tennessee-Schuylkill mine occur where the vein has changed to a more than average northwesterly strike."

Where gouge forms a large part of a vein-filling and is accompanied by striations and slickensides shear or slippage of the walls is indicated. However, layers and lenses of gangue and sulfide minerals commonly occur as open-space fillings within thick envelopes of this gouge. Slippage of gouge would not be conducive to the production of these open spaces. The most logical mechanism is pulling apart of the gouge by tensional stress. The occurrence of such fillings suggests that the veins have gone through an earlier slipping and a later pulling apart, and that the pulling apart coincided with a phase of sulfide deposition. A similar sequence at Pachuca, Mexico has been discussed by Wisser (52).

The paucity of sizable ore bodies might be due in part to the strong gouge filling of many veins. Further explanation might lie in a scarcity of metals in the hydrothermal solutions, in a lack of fissure structure that would produce openings during dislocation of the walls, or in insufficient pulling apart of the walls where that mechanism operated. The lack of suitable structure is open to question, however, as the majority of the veins have undergone only very shallow exploration. Detailed investigation of any single vein might reveal indications of favorable structures at depth.

Age and Genesis of Deposits.

Age.—The age of the mineralization is defined by the relations between the veins and the rhyolite and andesite dikes. It has been generally believed (23, p. 113) that the rhyolite dikes are younger than the ore deposits, but detailed mapping has failed to confirm this. In every place where a rhyolite dike and a vein have a clearly exposed contact the vein is later in age. Evidence consists of offsets of the dikes by the veins, thorough silicification of the rhyolite, and the presence of comb quartz and sulfide stringers within the dikes. No offset or truncation of a vein by a rhyolite dike was observed. The few small andesite dikes that were seen in association with the veins are hydrothermally altered and presumably are also pre-mineral in age, though such occurrences could be intra-mineral. If the assumption of a Tertiary age for the rhyolite and andesite dikes is valid the mineralization is of course Tertiary in age. The veins transect the disseminated copper mineralization, which is also younger than the volcanic dikes.

Genesis.—If possible, generalizations regarding the origin of an ore deposit should be made. Such generalizations must necessarily be based upon the observable relationships that exist between the geology and the mineralization of an area. In the Wallapai district certain features are significant, and they are listed as the framework for interpretation.

(1) Most obvious is the spatial association of mineralization with the Ithaca Peak porphyry stock of the Mineral Park district (Fig. 3). Disseminated sulfide mineralization is localized within this stock and is at the geographical center of the belt of fissure vein deposits. It is noteworthy that this general pattern of intrusion, associated disseminated copper mineralization, and superimposed and surrounding lead-zinc fissure deposits is repeated in many districts (13). Analogy is especially strong with the Bingham, Utah district where a center of mineralization has developed in one monzonite stock, whereas a nearby monzonite stock has no obvious relationship to the mineralization (37).

(2) Pre-intrusion structure was a factor in the emplacement of the Ithaca Peak porphyry. The Chloride district sill was injected into a steeply-pitching anticline, and folds guided at least part of the Mineral Park stock. No lines of shear or faulting were recognized that might have helped localize the intrusion, but post-intrusion stress is indicated by secondary foliation in the granite porphyry.

(3) The pattern of the veins was controlled by pre-vein structure. A strong northwest-trending joint system characterizes the region. Dikes both older and younger than the Ithaca Peak porphyry have followed these joints and show them to be features of long standing. Many of these joints became mineralized faults, and the majority of the veins follow this northwest trend. In the western part of the Chloride district the veins tended to form along fractures that are concordant with the anticlinal structure of that area, again a reflection of a pre-vein geologic feature.

(4) A period of unknown but presumably long duration separates both the disseminated sulfides and the fissure vein deposits from the time of intru-

sion of the Ithaca Peak porphyry. This period is indicated by the injection of pegmatite and aplite dikes, lamprophyre dikes, and andesite and rhyolite dikes, all of which came after the Ithaca Peak porphyry and preceded mineralization.

Interpretation of Relations.—On the basis of the commonly close areal relationship between ore deposits and intrusive igneous masses the inference is sometimes made that the mineralizing solutions have been expelled directly from those masses (14). A direct genetic connection between the Ithaca Peak porphyry and these ore deposits does not seem reasonable, however, owing to the time interval that elapsed between intrusion and mineralization, and because of the injection of a variety of dikes during that interval. The interposition of silicic and mafic satellitic dikes as a common occurrence in mining districts has been pointed out by Hulin (24). He showed by a statistical study that the usual sequence is (1) major intrusion, (2) silicic satellitic intrusions, (3) mafic satellitic intrusions, and (4) mineralization. The dikes are explained as differentiated magma facies which have come from some depth beneath the exposed major intrusion, and the mineralizing solutions are likewise attributed to a source at depth. This easiiy leads to the conclusion, drawn for example by Spurr (48) and Loughlin (31, p. 692), that the satellitic dikes and the mineralizing solutions have a common source and are merely drawn off at different times.

Similar reasoning might be applied to these Cerbat range deposits were it not for the complicating appearance of andesite and rhyolite dikes, apparently later in age than the satellitic dikes but still earlier than the mineralization. Even if the lamprophyres are assumed to be differentiation products of the Ithaca Peak porphyry, a matter of petrogenesis which is open to question (20), the interposition of the andesite and rhyolite dikes makes it difficult to believe that the mineralizing solutions have any genetic connection whatsoever with the Ithaca Peak porphyry.

Structural control seems to be the best explanation for the close areal association of the ore deposits with the Ithaca Peak porphyry. In a paper that further emphasizes pre-mineral diaschistic dike injection Hulin (25) stresses structural control as determining the association of intrusives and ore deposits. Disturbances during emplacement of an intrusion are held to prepare the ground prior to mineralization by weakening the invaded and overlying rocks and allowing relief of strain already present. Contraction due to solidification and cooling of the body is suggested as the cause of brecciation in porphyry copper deposits and also as the cause of recurrent fault movement that maintains permeability of a district during mineralization.

On the basis of the evidence that the vein pattern has been controlled largely by pre-vein structure, Hulin's proposal that intrusion emplacement weakens the invaded and overlying rocks, allowing relief of strain already present might be applicable. Such relief along the set of northwest-trending strong joint planes and along the fractures controlled by the anticline in the Chloride district may have served to block out the belt that was later mineralized. However, effects due to possible contraction are not so easily discov-

ered. Only part of the Mineral Park stock and none of the Chloride district sill was brecciated. As pointed out by Pennebaker (38, p. 130), local or special brecciation is not compatible with general shrinkage. Furthermore, large rhyolite dikes occur within the disseminated sulfide zone, and they are as thoroughly shattered as the surrounding granite porphyry. The intrusion was solidified prior to the intrusion of the dikes and was apparently cooled. Brecciation later in age than the rhyolite must be attributed to some cause other than shrinkage of the granite porphyry.

Recurrent faulting occurred after the emplacement of the Ithaca Peak porphyry and preceded mineralization, and intermittent movements occurred during the period of mineralization. It seems likely that the earlier faulting, especially that accompanying the injection of the lamprophyre dikes, could have resulted from intrusion shrinkage effects. The intra-mineral dislocations of the fissure vein deposits, however, following rhyolite dike injection and later in age than the disseminated sulfides, seem too remote in time to be a function of contraction of the Ithaca Peak porphyry.

Conclusion.—The association of the ore deposits with the intrusive stock of the Mineral Park district is too close to be fortuitous. Yet, apparently the intrusion has provided neither the mineralizing solutions nor complete structural control. Where cause and effect cannot be demonstrated between two related features the application of logic results in the treatment of both as effects of some other cause. Therefore, tectonic action is called upon, first to explain the localization of intrusion, and second to provide the locus of ore deposition. The presence of a major guiding channel for hydrothermal solutions is suggested by the symmetrical pattern of mineralization that has a distinct mineralogical center of disseminated sulfides and a structural center of brecciation. Tectonic action around this center, preceding and accompanying mineralization, is indisputable. The postulation that such a channel formed at an early stage of tectonic activity and thereby served to determine the general course of magmatic intrusion is not supported by direct evidence, The only obvious factors controlling intrusion are the folds in the invaded rocks. However, external stress was present after intrusion and may have preceded or accompanied it. The thesis of tectonic control for both intrusion and associated ore deposition is strengthened by the sequence of: (1) faulting, (2) intrusion along "conduit faults," (3) continued faulting, and (4) mineralization that has been described for other districts. Examples are Ely, Nevada (38, p. 131), Morenci, Arizona (11), and Magdalena, New Mexico (31, pp. 688–689).

DISSEMINATED SULFIDE DEPOSIT.

An observer approaching from the west cannot fail to be impressed by the reddish colored cluster of peaks that mark the Mineral Park district. Inspection shows that the color comes from an iron-stained capping that lies over a thoroughly fractured and mineralized portion of Ithaca Peak granite porphyry. Closer inspection reveals that the mineralization is of the well-known disseminated or "porphyry copper" type.

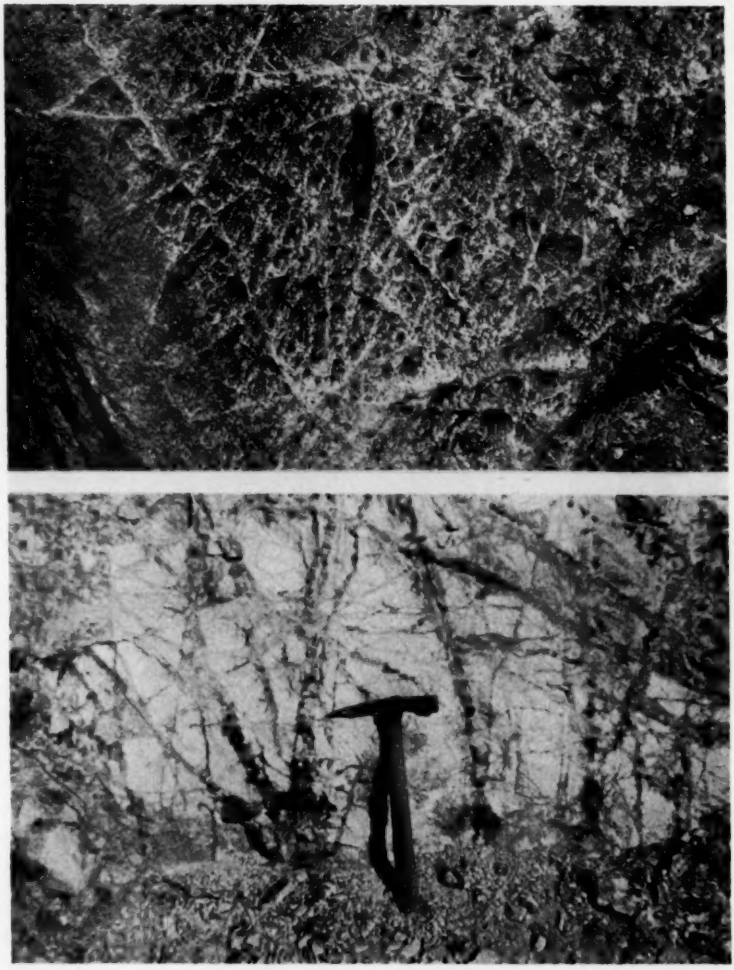


FIG. 11. Quartz-sulfide veinlets in "porphyry copper" mineralization. (Upper) Exposure in canyon bottom, west central part of S 24, T 23 N, R 18 W. (Lower) Road cut, southeast corner of S 24, T 23 N, R 18 W. Dark stains are limonite.

Distribution of Mineralization.—An area of more than four square miles in the northeastern portion of the Ithaca Peak porphyry intrusive stock has been outlined (Fig. 3) as containing the rocks that are most strongly shattered and mineralized. This is an arbitrary outline, as the degree of mineralization varies within the borders, and the outer limits are gradational rather than sharp. Also, strong mineralization may occur locally outside this main brecciated mass. An example is the thick tongue of porphyry that extends through Union Basin to the Golconda mine. This tongue is strongly fractured and has a reddish-brown capping. The mineralization is chiefly contained within the Ithaca Peak porphyry, but in places the mineralization passes across the intrusive contact into the Precambrian Cerbat schist and gneiss. In the canyon north of Mineral Park signs of mineralization were traced outward 1,000 feet into granite gneiss. Large rhyolite dikes which traverse the Ithaca Peak porphyry are mineralized, as are septa and pendants of Precambrian schist and gneiss.

Features of Hypogene Mineralization.—The primary minerals consist of abundant quartz and pyrite and minor amounts of chalcopyrite and molybdenite. A few specks of bornite were observed in one specimen. As is typical in this type of deposit, these minerals occur both as fracture fillings and as specks and grains scattered through unfractured rock. Sphalerite and galena occur in a few places in small veinlets, which seem to be younger than the other veinlets. The sphalerite and galena are believed to be the same age as the large fissure-vein deposits of lead and zinc that cut across the disseminated sulfide deposit.

The strongly mineralized areas coincide with thoroughly shattered rock, where entry of hydrothermal solutions and the formation of closely spaced veinlets has been possible. The veinlets in many of these areas are separated by only a fraction of an inch, and individual blocks of rock are rarely more than a few inches across. The fracture pattern is an intricate network, which rarely shows displacements at intersections. Observations made at widely separated places within the main mineralized area suggest that the strongest veinlets favor strikes west-northwest and east-northeast. In detail, however, the veinlets seem to follow every conceivable strike and dip (Fig. 11).

The veinlets commonly range from one-quarter inch in thickness down to mere seams. However, thicknesses of an inch or more are not rare. The larger veinlets typically contain vugs between crystals of quartz and pyrite.

Veinlets of quartz and pyrite that cut veinlets of quartz, pyrite and molybdenite suggest that molybdenite was introduced in an early stage. Chalcopyrite and the few specks of bornite that were observed in polished section characteristically occur as blebs within pyrite and seem to be later in age. Some of the chalcopyrite, however, occurs as individual grains in the rock and in veinlets, and this chalcopyrite seems to be contemporaneous with quartz and pyrite.

Hydrothermal Alteration.—The most obvious change caused by the mineralizing solutions was silicification of the rocks. The walls of veinlets are commonly impregnated with quartz, and several large areas were so effectively hardened by silica that they have eroded into rough, craggy peaks.

Sericite was formed almost as abundantly as quartz, and many rocks seem in hand specimen to consist entirely of quartz, sericite, and scattered grains of pyrite. Numerous specimens contain clay mineral, but much of this may be supergene in origin. Ferro-magnesian minerals have been completely removed from the strongly altered areas, and the rocks are now white to yellowish gray in color.

A specimen containing fresh sulfides, from the Ostrich shaft in Mineral Park, was examined in thin-section. This rock contains approximately 70 percent granular quartz and 30 percent sericite. Minor amounts of clay mineral are associated with the sericite and seem to have formed contemporaneously with it. Rutile is present both as sagenite webs and as crystals, which are commonly in clusters. In one place rutile was observed replacing sphene. Some of the quartz corrodes and is later than pyrite, and sericite replaces much early quartz. Late pyrite partly replaces some of the sericite.

Oxidation and Secondary Enrichment.—The highly pyritic mineralization has assured a potent supply of strongly oxidizing solutions. As a result the surface capping is largely devoid of sulfide minerals but contains abundant residual "limonite." The quantity of iron sulfate produced through oxidation of the pyrite is emphasized by the common occurrence of iron oxide-cemented talus and alluvium. Stream terrace deposits as much as 20 feet thick have been bound into dark reddish-brown conglomerate and the bottoms of stream courses are in places covered with a cemented blanket of rubble a few inches to two feet thick.

Oxide minerals of copper occur in a few places. Malachite is most common, staining oxide zone rocks. Small seams of malachite and azurite were seen in a few prospect pits. A specimen of alluvium collected near the mouth of a prospect tunnel in Bismark canyon contains a cement of cuprite, native copper, and malachite. Arborescent plates of native copper were collected from the dump of another tunnel in the same canyon, and iron-copper chalcanthite occurs on the walls of this tunnel.

Some polished sections show the development of supergene sulfides. In these sections chalcopyrite is surrounded by rims of covellite and chalcocite, and pyrite is replaced by chalcocite and minor amounts of covellite.

An indication of the depths of oxidation and secondary enrichment is given by the logs of three churn drill holes that were put down in the peak northeast of Gross ranch in 1915. The leached zone, which carried only traces of copper, was recorded to depths of 170, 180, and 290 feet. The enriched zone reached depths respectively, of 410, 520, and 340 feet.

Age and Genesis.—The shattering and mineralization took place after the injection of the rhyolite dikes. The mineralization was a late geologic event but was the first phase of the general metallization of this region. Disseminated sulfide mineralization preceded the lead-zinc mineralization of the more widely distributed fissure veins, and disseminated sulfides occupy a central position in the vein belt. Furthermore, the occurrence of sphalerite and galena in small veinlets that are intimately associated with the disseminated sulfides suggests a close relationship between the two types of mineralization. Fea-

tures pertaining to the origin and localization of the deposits have been discussed in the preceding section on ore genesis.

TURQUOISE DEPOSITS.

Deposits of turquoise have been exploited on both the south and north sides of Aztec Mountain, and on all sides, from top to bottom, of Ithaca Peak. Minor workings occur in the ridge just south of the entrance to the Mineral Park basin.

Mode of Occurrence.—Turquoise deposits are restricted to the intrusive stock of Ithaca Peak porphyry and occur within the altered and leached capping that overlies the deposit of disseminated sulfides. It is perhaps significant that the turquoise has formed in those portions of the capping that are most highly silicified and sericitized and which have eroded into rough peaks and ridges.

Turquoise is present mostly in seams and veinlets and commonly fills vugs and cavities in earlier quartz. Lenses and kidneys have formed in places in wide veinlets and within masses of sericite and clay mineral. Detailed descriptions of the grade and manner of occurrence of turquoise in the various claims have been given by Sterrett (49). Associated minerals are those which would be expected to form from the hypogene alteration, disseminated sulfide mineralization, and supergene leaching of granite porphyry. The minerals include quartz, sericite, clay mineral, hydrous iron oxide, malachite, and chrysocolla. In a thin-section of a specimen from Ithaca Peak turquoise occurs as discontinuous veinlet segments, associated with what seem to be contemporaneous segments of goethite and jarosite.

All the workings are surficial in nature, and much of the mining has been by open-cut methods. Narrow benches have been cut in many of the steep slopes of Ithaca Peak, and working faces as much as 50 feet high have been carried progressively back into the mountain.

Origin.—There is general agreement that turquoise is a mineral of secondary origin. It is variable in composition but is usually stated as $CuO \cdot 3Al_2O_3 \cdot 2P_2O_5 \cdot 9H_2O$. Ball (2) classes it as having formed by "descending oxidizing water," and a convincing analysis by Paige (36) leads to the conclusion that it is the result of supergene processes. Such an origin is compatible with the features of the Mineral Park deposits, as they are analogous to the deposits discussed by Paige. Their restriction to the leached "porphyry copper" capping is suggestive of a secondary origin, and the close association in time of turquoise, goethite, and jarosite is strong confirmatory evidence. The source of the necessary solutions and the probable chemical action involved have been discussed fully by Paige.

EMERALD ISLE COPPER DEPOSIT.

The Emerald Isle copper deposit is located in the Sacramento Valley half a mile from the west face of the Cerbat Range. It is approximately 3 miles south of the town of Chloride and 15 miles northwest of Kingman. Its geologic setting is an alluvium covered pediment, which in this area is cut in

Ithaca Peak granite porphyry. The relief is low and undulatory, partly from initial irregularities in the pediment surface, which are expressed by protruding knobs and ridges of bedrock, but mostly from recent erosional dissection. The mine is on a northeast-trending low ridge which has an alluvial veneer of variable thickness.

Nature of the deposit.—The deposit consists of a mineralized blanket of alluvium and a fissure vein. The vein cuts not only the granite porphyry bedrock but also the overlying alluvium. Minor fissures and veinlets occur parallel to the main vein and likewise extend from bedrock into alluvium. The principal copper mineral in both blanket and veins is chrysocolla. The resulting green color of the mineralized ground explains the appropriate name of the deposit.

Blanket Mineralization.—Copper has been added to the blanket by the deposition of copper-silicate minerals in the pore spaces of the highly permeable alluvium. Dioptase ($CuSiO_3 \cdot H_2O$) has been reported as constituting several percent of the ore (21), but the principal mineral seems to be chrysocolla ($CuSiO_3 \cdot 2H_2O$). The copper-silicate material ranges from pale blue-green to moderate blue-green in color. Associated with this green material is a brittle shiny black substance that yields copper when reduced with soda and charcoal under the blow pipe. It is perhaps best classed as "copper pitch," though it might be a variety of chrysocolla. It is possible that much chrysocolla is composed of variable amounts of copper oxide, silica, and water (15), and differences in color and properties are to be expected. The presence of impurities would also affect the nature of the mineral. "Chrysocolla" will be used here in a broad sense that will imply variations and also the presence of dioptase.

The chrysocolla forms a cementing matrix for the alluvial detritus. Chrysocolla occurs chiefly in the form of microscopic acicular crystals, packed into narrow vermiform bands, but in places it forms hemispherical or spherical radiating groups. The texture is a delicate crustification type that could only form by deposition of successive thin layers. A minor amount of the chrysocolla is cryptocrystalline, which, at least in part, represents an early stage of deposition, for the acicular bands have formed upon, around, and intruding into the cryptocrystalline material. The open spaces in the alluvium were not everywhere completely filled, and the chrysocolla in some places has a finely botryoidal surface.

Scales and films of brown to black copper oxide are common on the surface of the chrysocolla. These may be earthy or have a distinct metallic luster and can be classed as either melaconite or tenorite.

The limits of mineralization in the alluvial veneer have not been determined but present workings suggest a minimum extent of 10 acres. Exposures in the open pit at the mine contain an assemblage of sand, gravel, cobbles, and boulders, which are poorly sorted but coarsely bedded. The strike of the bedding is approximately east and the dip 4 degrees south.

Vein Mineralization.—The principal vein strikes N 30° E, cutting through the mineralized blanket. In its uppermost portions the vein is vertical or dips steeply north, but dips of 45 degrees north have been reported in some of the

lower workings. The vein ranges from 3 to 12 feet in width. Alluvium occupies both walls at and near the surface. At depths as little as 25 feet, however, bedrock occurs in the footwall, and alluvium occurs in the hanging wall. The amount of displacement was not determined.

Early development work at the mine was confined largely to the vein. Two short shafts were sunk and lateral underground workings are reported to total 1,600 feet, chiefly at the 100 foot level (34). An average copper content of 3½ percent is reported for all these workings and an average of 6½ percent for the main drift, which apparently was driven within the vein.

The mineralogy of the vein is identical with that of the blanket, and in a winze 40 feet below the 100 level the ore values were apparently still furnished by chrysocolla. In the upper portions of the vein the filling between the walls consists of cemented alluvium that is analogous to the adjacent blanket, except that the vein has a higher copper content. The walls are distinct, roughly rolling, show effects of shear, and in places are lined with small amounts of gouge. Seams of delicately banded chrysocolla characteristically line both walls, and other strong seams occur in the interior of the vein. An exposure of the vein, where it was encountered in open pit excavation, is shown in Figure 8.

Where bedrock was observed in the footwall the vein filling still consisted of cemented alluvial detritus. The nature of the vein where bedrock occurs in both walls is not known. Specimens of granite porphyry from the foot wall are leached and thoroughly altered, and tiny irregular veinlets of chrysocolla occur in the rock. In thin section the principal minerals are seen to be abundant clay mineral, sericite, and brown chlorite.

Minor Fractures.—In the south face of the open pit, as it existed in June, 1948, a zone of mineralized irregular fractures was exposed. This zone extended eastward from the main vein for 100 feet, at which point the pit walls were caved. The seams and veinlets were spaced from 1 to 10 feet apart, were all essentially vertical and had strikes roughly parallel to the main vein. Thirty-five feet east of the main vein a knob of bedrock was exposed at the bottom of the face, and the chrysocolla-filled fractures were observed to pass into the bedrock. Some of the veinlets showed slight displacements, but most seemed to be dilation fractures. Some extended to the surface, others died out upward.

Age and Genesis.—The mineralization, occurring as it does in a blanket of alluvium and in a fissure vein that passes from a rock pediment into alluvium, is dated as Quaternary. There has been some recent dissection of the pediment area, but terrace levels in the mountains indicate that 50 feet would be a maximum for any former cover. If the deposit had formed prior to Quaternary time a thicker cover would be expected; and the mountain front should have migrated farther back from the mineralized portion of the pediment.

It has been suggested that the mineralization was by solutions derived from the weathering of the "porphyry copper" deposit of the Mineral Park district. This would involve gravitative transfer of the solutions and localized deposition of chrysocolla around and within a strong fissure vein and associ-

ated fractures. Such solutions could exist, but the concentration of copper in them would be negligible, and there are no plausible reasons to explain the concentration and deposition of the copper at this particular location and within a vein.

On the other hand, solutions ascending along fissures and spreading out into the alluvium provide a simple and logical source for the copper. Assuming this to have happened, the question arises as to the nature of the chrysocolla. This mineral is usually supergene and is a secondary product of various primary copper-bearing minerals. In the Emerald Isle deposit, however, the following points suggest that the chrysocolla is primary:

(1) There are no relict grains of sulfides, or any minerals, which might have served as a primary source of the copper. It might be assumed that replacement or solution of such primary minerals was complete, but at least a few specks should have been preserved here and there.

(2) The texture of the chrysocolla, both in vein and blanket, is delicately banded and crustified, which suggests that formation was by open space filling and not replacement. If the chrysocolla is supergene the logical source of the copper would be at some higher level. If there were primary mineralization above, however, furnishing the source of copper solutions, there should have been primary mineralization at the present levels, at least in the vein. This would have to be leached completely away, before the solution of overlying material, in order to explain the lack of relict primary minerals and replacement textures. Such a sequence does not seem feasible.

(3) Some of the veinlets pinch out upward. The chrysocolla filling apparently was deposited by ascending solutions. Perhaps the veinlets could be explained by lateral secretion, but the primary source material would still be missing.

From the above considerations it is concluded that the mineralization has resulted from deposition of chrysocolla by ascending hypogene solutions that rose along one large and many small fissures and spread out into the adjacent alluvium. The conclusion is supported by the fact that the deposit was formed under essentially surface conditions. The main fissure and some of the associated minor fractures undoubtedly reached the original surface. In such an environment ascending hypogene solutions would be under the same pressures and could very easily have the same temperatures as the supergene solutions that deposit chrysocolla. And there is no reason why copper and silica could not be present in the proper amounts to form chrysocolla from such hypogene solutions.

CALIFORNIA INSTITUTE OF TECHNOLOGY,
PASADENA, CALIF.
August 15, 1949.

BIBLIOGRAPHY.

1. Anderson, C. A., Structural control of copper mineralization, Bagdad, Arizona: Mining Technology A.I.M.E., Tech. Pub. 2352, p. 8, March 1948.
2. Ball, S. H., The geologic and geographic distribution of precious stones: ECON. GEOL., vol. 17, no. 7, p. 584, 1922.

3. Bastin, E. S., Origin of certain rich silver ores near Chloride and Kingman, Arizona: U. S. Geol. Survey Bull. 750, pp. 17–39, 1925.
4. ——, Paragenetic relations in the silver ores of Zacatecas, Mexico: Econ. Geol., vol. 36, no. 4, pp. 373–376, 1941.
5. Bastin, E. S., et al, Criteria of age relations of minerals: Econ. Geol., vol. 26, no. 6, pp. 561–610, 1931.
6. Bateman, A. M., Economic mineral deposits, p. 245, John Wiley & Sons, Inc., New York, 1942.
7. Billings, M. P., Structural geology, pp. 116–119, Prentice-Hall, Inc., New York, 1942.
8. Blanchard, R., Leached derivatives of arsenopyrite and chromite: Econ. Geol., vol. 37, no. 7, pp. 596–626, 1942.
9. Boswell, P. F., and Blanchard, R., Oxidation products from sphalerite and galena: Econ. Geol., vol. 22, no. 5, pp. 419–453, 1927.
10. Butler, B. S., Influence of the replaced rock on replacement minerals associated with ore deposits: Econ. Geol., vol. 27, no. 1, pp. 1–24, 1932.
11. Butler, B. S., and Wilson, E. D., Clifton-Morenci district, *in* Some Arizona ore deposits: Arizona Bur. Mines Bull. 145, p. 74, 1938.
12. Elsing, M. J., and Heineman, R. E. S., Arizona metal production: Arizona Bur. Mines Bull. 140, 1936.
13. Emmons, W. H., Relations of the disseminated copper ore in porphyry to igneous intrusives: Am. Inst. Min. Met. Eng. Trans., vol. 75, p. 807, 1927.
14. ——, On the mechanism of the deposition of certain metalliferous lode systems associated with granitic batholiths, *in* Ore deposits of the Western States, p. 327, Am. Inst. Min. Met. Eng., 1933.
15. Ford, W. E., Dana's textbook of mineralogy, 4th edition, p. 686, John Wiley & Sons, New York, 1932.
16. Garrett, S. K., *in* Some Arizona ore deposits: Arizona Bur. Mines Bull. 145, pp. 117–119, 1938.
17. Gillson, J. L., Granodiorites in the Pend Oreille district of northern Idaho: Jour. Geology, vol. 35, pp. 1–31, 1927.
18. Graton, L. C., The hydrothermal depth-zones, *in* Ore deposits of the Western States, pp. 181–197, Am. Inst. Min. Met. Eng., 1933.
19. Graton, L. C., and Bowditch, S. L., Alkaline and acid solutions in hypogene zoning at Cerro de Pasco: Econ. Geol., vol. 31, no. 7, pp. 655–667, 1936.
20. Grout, F. F., Criteria of origin of inclusions in plutonic rocks: Geol. Soc. America Bull., vol. 48, p. 1549, 1937.
21. Hanley, H. R., Rolla, Missouri, personal communication, 1949.
22. Haury, P. S., Examination of zinc-lead mines in the Wallapai mining district, Mohave County, Arizona: U. S. Bur. Mines Rept. Inv. 4101, p. 4, 1947.
23. Hernon, R. M., *in* Some Arizona ore deposits: Arizona Bur. Mines Bull. 145, Geol. Series No. 12, pp. 110–117, 1938.
24. Hulin, C. D., Ore genesis and ore shoots: Eng. and Min. Jour., vol. 127, pp. 228–230, 1929.
25. ——, Factors in the localization of mineralized districts: Mining Technology, A.I.M.E. Tech. Pub. 1762, 1945.
26. Jaffe, H. W., Reexamination of sphene: Am. Mineralogist, vol. 32, pp. 637–642, 1947.
27. Krieger, Philip, Notes on an X-ray diffraction study of the series calcite-rhodochrosite: Am. Mineralogist, vol. 15, pp. 24–26, 1930.
28. Lee, W. T., Geologic reconnaissance of a part of western Arizona: U. S. Geol. Survey Bull. 352, 1908.
29. Lindgren, Waldemar, Mineral deposits, 4th edition, McGraw-Hill Book Co., Inc., New York, 1933.
30. Locke, Augustus, Leached outcrops as guides to copper ore, p. 64, Williams and Wilkins Co., Baltimore, 1926.
31. Loughlin, G. F., Comments on the origin and major structural control of igneous rocks and related mineral deposits: Econ. Geol., vol. 36, no. 7, pp. 671–697, 1941.
32. McEntee, F. J., Jr., and Zlatnik, D. F., Mineral Park Milling Co., personal communication, 1948.
33. McKinstry, H. E., Mining geology, pp. 305–306, Prentice-Hall, Inc., New York, 1948.
34. Mohave County Miner, Boulder Dam edition, Kingman, Arizona, 1929.
35. Newhouse, W. H., Time sequence of hypogene ore mineral deposition: Econ. Geol., vol. 23, no. 6, p. 651, 1928.
36. Paige, Sidney, The origin of turquoise in the Burro Mountains, New Mexico: Econ Geol., vol. 7, no. 4, pp. 382–392, 1912.
37. Peacock, Hollis, An outline of the geology of the Bingham district: Mining and Metallurgy, vol. 29, pp. 533–534, 1948.

38. Pennebaker, E. N., The Robinson mining district, *in* Ore deposits as related to structural features, pp. 128–131, Princeton Press, 1942.
39. Ransome, F. L., Geology of the Globe copper district, Arizona: U. S. Geol. Survey Prof. Paper 12, p. 15, 1903.
40. Ross, C. S., and Kerr, P. F., The kaolin minerals: U. S. Geol. Survey Prof. Paper 165–E, pp. 157–158, 1930.
41. Sahama, Th. G., On the chemistry of the mineral titanite: Comm. géol. Finlande Bull. 138, pp. 88–120, 1946.
42. Sales, R. H., The localization of values in ore bodies and the occurrence of shoots in metalliferous deposits: Econ. Geol., vol. 3, no. 4, p. 326, 1908.
43. Sales, R. H., and Meyers, C., Wall rock alteration at Butte, Montana: Mining Technology A.I.M.E., Tech. Pub. 2400, p. 14, 1948.
44. Schmedeman, O. C., Notes on the chemistry of ore solutions: Econ. Geol., vol. 33, no. 8, pp. 803–805, 1938.
45. Schrader, F. C., Mineral deposits of the Cerbat Range, Black Mountains, and Grand Wash Cliffs, Mohave County, Arizona: U. S. Geol. Survey Bull. 397, 1909.
46. Schwartz, G. M., Hydrothermal alteration of igneous rocks: Geol. Soc. America Bull., vol. 50, pp. 195–197, 1939.
47. ——, Progress in the study of exsolution in ore minerals: Econ. Geol., vol. 37, no. 5, pp. 363–364, 1942.
48. Spurr, J. E., Diaschistic dikes and ore deposits: Econ. Geol., vol. 34, no. 1, pp. 41–48, 1939.
49. Sterrett, D. B., Precious stones, *in* Mineral Resources of the United States, Part II, pp. 847–852, U. S. Geol. Survey, 1908.
50. Thomas, B. E., Geology and ore deposits of the Wallapai district, Arizona: Calif. Inst. of Technology, Ph.D. thesis, 187 pp., 1949.
51. Minerals Yearbooks, U. S. Bur. Mines, 1934–1946.
52. Wisser, Edward, The environment of ore bodies: Am. Inst. Min. Met. Eng. Trans., vol. 144, pp. 108–109, 1941.

GEOCHEMICAL PROSPECTING FOR ORES: A PROGRESS REPORT.

H. E. HAWKES.[1]

ABSTRACT.

Methods of prospecting for mineral deposits by means of chemical studies of residual soil, alluvium, glacial moraine, vegetation, and natural water were first applied on a systematic scale in Scandinavia and Russia about 15 years ago. Since the war, work in this field has been undertaken by several independent groups in the United States and Canada, including the Geochemical Prospecting Unit of the U. S. Geological Survey.

Best results have been obtained by systematic analysis of zinc in residuum, ground water, and vegetation; copper and lead in gossan and residuum; tin in residuum and alluvium; molybdenum in residuum; and cobalt, nickel, and gold in vegetation. In addition, studies of plant ecologies and toxicity symptoms in vegetation in relation to metal-rich soil appear to be promising.

Rapid colorimetric and spectrographic tests for traces of metals in soil, water, and vegetation have been developed for use under field conditions.

INTRODUCTION.

THE development within recent years of new chemical techniques for measuring extremely small traces of the less common elements in naturally occurring material has given the practical geologist a powerful new tool. One of the more promising applications of these new techniques is in mineral exploration. By systematic analysis of rocks, weathered outcrops, residual soil, alluvium, vegetation, or water, it has been found possible to detect patterns of dispersed metals around or above deposits of ore that otherwise gave no clue to their presence. Geochemical dispersion patterns associated with ore bodies are likely to be of very considerable extent as compared with the ore itself, and will provide a correspondingly larger "target" for the prospector to shoot at.

Geochemical dispersion patterns associated with ore deposits may be formed either: (1) at the time of formation of the deposit when primary halos of the metals are dispersed in the country rock by ore-forming solutions, or (2) during the time the deposit is in the zone of weathering at the earth's surface when secondary dispersion patterns are formed in weathered outcrops, soils, vegetation, and surface water.

This paper is an attempt to summarize very briefly the present status and achievements of the work on secondary dispersion patterns without touching on the basic principles in any detail. A discussion of primary dispersion patterns is also omitted. For a fuller treatment of some of the principles and

[1] Published by permission of the Director, U. S. Geological Survey, and presented before the Society of Economic Geologists, San Francisco, February, 1949.

techniques of geochemical prospecting for ores, the reader is referred to papers by Sergeev (32),[2] Thyssen (39), Rankama (26), Sokoloff (36), and Hawkes (8).

HISTORICAL SKETCH.

Mineralogical studies of secondary dispersion patterns as a prospecting method constitute a well-established method of ore finding, as panning of alluvium and surface wash for resistant ore minerals has led to the discovery of innumerable lode deposits of gold, tin, tungsten, and many other metals. Chemical analysis, as distinguished from mineralogical observations, was not applied in these problems on a large scale until the early experiments by Soviet geologists about 1932. Since then geochemical techniques have been developed and applied on an increasing scale in Russia with apparently considerable success. In the middle thirties Swedish investigators independently developed techniques of plant sampling and analysis as a prospecting method, and applied them with some success up to the outbreak of the war. Within the last few years research on geochemical prospecting methods has been undertaken on this continent by the U. S. Geological Survey and by several private groups in mining companies and university laboratories.

SUMMARY OF PROGRESS.

Table I presents in highly condensed form a qualitative appraisal of methods of prospecting based on chemical studies of secondary dispersion patterns. The data are arranged according to the ore metal and the material serving as host to the dispersed ore metal. In detail, the course of migration of an element in the zone of weathering as it passes from one host to the next is complicated in the extreme, but the general trend is one of progressive dilution as it travels away from its source in the parent rock or ore. With increasing distance from the source, the concentration of the ore metal approaches the "background level" of metal derived from the weathering of normal unmineralized rock.

Dispersion patterns may take different forms, indicated in the second vertical column of Table I, depending on the manner in which the metal migrates in or through the host material. A "halo" is a more or less symmetrical pattern centered around the bedrock deposit. A "fan" is a one-sided distribution pattern, diverging away from the source of metal. A "train" is a pattern that follows a well-defined system of channels, usually the surface drainage.

The appraisals expressed by the symbols in Table I are supported either by published reports or by the results of unpublished investigations by the Geological Survey since 1946. The intention has been to define the symbols in such a way that the subjective element is reduced to a minimum. Nevertheless, the writer is well aware that a considerable element of personal opinion still remains, stemming in part from interpretations presented in the original reports and in part from the present writer's appraisal of the reports. This is

[2] Numbers in parentheses refer to Bibliography at end of paper.

TABLE I.

SUMMARY OF PROGRESS, GEOCHEMICAL PROSPECTING FOR ORES.

Host material	Dispersion pattern	Zn	Cu	Pb	Sn	W	Mo	Ni	Cr
Gossan	Residual pattern	N	G	G	0	0	0	0	0
Residual soil from carbonate rocks	Residual pattern; halo	G	0	G	0	0	0	0	0
Residual soil from silicate rocks	Residual pattern; halo	G	G	G	G	P	G	P	P
Alluvium	Train	0	P	0	G	0	0	0	0
Glacial moraine	Fan	P	P	P	0	0	0	0	0
Bogs	Secondary accumulation	G	P	0	0	0	0	0	0
Ground water	Fan; train	G	P	N	0	0	0	0	0
Surface water	Train	P	P	N	0	0	0	0	0
Accumulator plants	Halo; train	G	P	P	G	G	0	P	P
Indicator plants[1]	Halo; train	P	P	P	P	0	0	0	0

G = good: Has indicated presence of known or subsequently discovered ore that was completely hidden by superficial cover.

P = promising: Has indicated presence of outcropping ore.

N = negative: Has generally failed to indicate presence of known ore.

0 = no experiments to date.

[1] "Indicator plants" show the presence of exceptionally high concentrations of metal by diagnostic organic symptoms or by growth habits.

especially true of the Russian work, where no personal contact could be established either with the authors or with the results of their work.

Following is a tabulation of references and source material supporting Table I, together with reports of results on several additional elements not listed in the table.

Gossan.—Copper in gossan over primary copper deposits in the western United States (3); copper, gold, silver, arsenic, lead, and zinc in gossans of the western United States (18); copper and lead in weathered ore outcrops in Russia (13); lead, gold, and arsenic in gossans over Australian galena-arsenopyrite deposits (2).

Residual Soil from Carbonate Rocks.—Zinc in residual soil over the Friends Station, Tenn., zinc deposit (9); zinc and lead in residuum over lead fissures in southwestern Wisconsin zinc district (unpublished data, Geological Survey).

Residual Soil from Silicate Rocks.—Zinc, lead, and copper in residual soil over an undeveloped part of the Union Copper Mine, Cabarrus County, N. C. (unpublished data, Geological Survey); copper over San Manuel copper deposit, Ariz. (20); copper, lead, tin, tungsten, molybdenum, nickel, cobalt, chromium, manganese, sulfate, and borate in surface soils over Russian deposits (6, 12, 23, 31, 32, 34, 40).

Alluvium.—Copper in alluvium derived from San Manuel copper deposit, Ariz. (20); tin in alluvium derived from Russian deposits (6, 30).

Glacial Moraine.—Copper, lead, and zinc in glacial till in the Røros district, Norway (42, 43, 44); zinc in glacial till in Edward-Balmat zinc district, N. Y.; and copper in glacial material in northern Michigan (unpublished data, Geological Survey).

Bogs.—Copper in peat bogs downstream from ore in Wales, Montana, and Michigan (7, 19, 24; unpublished data, Geological Survey); zinc in peat bogs near Manning, Orleans Co., N. Y. (37; unpublished data, Geological Survey).

Ground Water.—Zinc in spring water in southwestern Wisconsin zinc district, and zinc in well water near Manning, Orleans, Co., N. Y. (unpublished data, Geological Survey); copper in drill-hole water at San Manuel copper deposit, Ariz. (20); copper, lead, and zinc in mine water in Colorado and Utah (11).

Surface Water.—Zinc, copper, and lead in surface water draining Colorado mines (11); zinc and copper in surface water draining mines at Butte, Mont. (15); heavy metals in surface water draining Berezov mine, Russia (33); sulfate and copper in surface waters draining sulfide mines of Røros area, Norway (41, 47).

Accumulator Plants.—Zinc in vegetation growing on zinc-rich peat bogs near Manning, Orleans Co., N. Y. (37; unpublished data, Geological Survey); zinc in vegetation growing on zinc-rich mill tailings at Friedensville, Pa. (29); zinc and copper in plants growing over ore in British Columbia (48, 49, 51); copper, lead, and zinc in plants growing over ore in the Røros district, Norway (45, 46); zinc, tin, and tungsten in vegetation over mines in Cornwall, England (21, 38); nickel and cobalt in vegetation over Russian nickel deposits (23); nickel in vegetation over Finnish nickel deposit (25); and zinc, copper, and silver in plant ash over Swedish lead-zinc deposit (10); gold in vegetation over gold deposits (22, 50).

Indicator Plants.—Indicator plants reported for zinc, copper, lead, tin, gold, silver, mercury, and many nonmetallic elements (1, 4, 16, 17).

It should be pointed out that studies of the metal content of water draining known mines may be misleading, as the accelerated oxidation resulting from opening up a deposit will cause many times more metal to be discharged into the drainage than would come from the same deposit in its original undisturbed state. Thus it is hardly fair to appraise water sampling as a prospecting method until there are more data from deposits that have not been artificially exposed.

ANALYTICAL TECHNIQUES.

For effective large-scale geochemical prospecting, the routine analytical procedures should be rapid, cheap, semiquantitative, and capable of mass production. Portability is a desirable feature in that the analytical work may then be done either directly in the field or in temporary field headquarters, and the results made immediately available as a guide in following the geochemical indications.

Methods that meet these specifications fall into a relatively undeveloped field of analytical chemistry midway between conventional qualitative and quantitative analysis. Spectrographic and colorimetric methods have been most successful in applied geochemical prospecting work to date.

Spectrographic Analysis.—Both the Russian and the Swedish work depend largely or entirely on spectrographic analysis. Soviet physicists have developed a portable spectrograph that can be disassembled and carried by truck or pack animal to the field headquarters (5, 27). Daily productivity is in the order of 100 spectograms of soil by a seven-man crew. This includes sample preparation and preparation of the spectrograms without interpretation (32).

Swedish geochemical prospecting work was serviced by a laboratory spectrograph capable of turning out 40 spectrograms of plant ash by a four-man crew per day (J. Ecklund and S. Landergren, personal communication).

Colorimetric Analysis.—Modifications of standard colorimetric methods for traces of metals have been developed by the Geological Survey for field analysis of heavy metals in water (11) and for zinc in soil (14) and in vegetation (28). Productivity of the latter two methods is in the order of 30 zinc determinations per man-day. Colorimetric methods for geochemical field work have also been developed in Russia, but the Russian authors do not indicate how generally these methods have been applied to practical problems (32).

Other Methods.—A modification of standard spot tests for copper and nickel has been developed by the Geological Survey for geochemical prospecting work, but has not yet been applied to large-scale problems. Microchemical methods similar to those described by Short (35) show promise for special problems. Chromatographic, turbidimetric, polarographic, and electrolytic methods have also been considered for field or laboratory methods of geochemical prospecting.

CONCLUSIONS.

Applied and experimental geochemical prospecting work in Russia, Sweden, and this country indicate that the methods show considerable promise and deserve intensive research. It is too early to forecast the ultimate place that geochemical methods will have in our repertoire of prospecting tools. In the early stages of development of any new technique it is easy to become too enthusiastic and to place more confidence in the new methods than they deserve. Geophysical methods of prospecting for ores were overpromoted during the early days of their use, and as a result received a bad name that still lingers. With some wisdom and judgment it should be possible to avoid a similar fate for geochemical prospecting.

U. S. Geological Survey,
Geochemical Prospecting Unit,
Washington 25, D. C.
July 18, 1949.

BIBLIOGRAPHY.

1. Beck, Richard, The nature of ore deposits, vol. 2, translated by W. H. Weed, published by Eng. and Min. Jour., New York, 1905.
2. Blanchard, Roland, Leached derivatives of arsenopyrite and chromite: Econ. Geol., vol. 37, p. 612, 1942.
3. Blanchard, Roland, and Boswell, P. F., Notes on the oxidation products derived from chalcopyrite: Econ. Geol., vol. 20, p. 627, 1925.
4. Dorn, Paul, Pflanzen als Anzeichen für Erzlagerstätten: Der Biologe, vol. 6, pp. 11–13, Munich, 1937.
5. Fersman, A. E., Geochemical and mineralogical methods of prospecting for useful minerals (in Russian): Izd. Akad. Nauk, Moscow-Leningrad, 1939.
6. Flerov, B. L., On methods of prospecting primary tin deposits (in Russian): Sovet. Geol. vol. 8, no. 10, pp. 63–81, 1938.
7. Forrester, J. D., A native copper deposit near Jefferson City, Montana: Econ. Geol., vol. 37, pp. 126–135, 1942.
8. Hawkes, H. E., Geochemical prospecting for ores: Symposium on sedimentation, in press, 1949.
9. Hawkes, H. E., and Lakin, H. W., Vestigial zinc in surface residuum associated with primary zinc ore in East Tennessee: Econ. Geol., vol. 44, pp. 286–295, 1949.
10. Hedström, H., and Nordström, A., Malmletningsteknikens nuvarande ståndpunkt: Meddelanden från Jernkontorets Gruvbyrå (Upsala), vol. 39, pp. 6–10, 1945.
11. Huff, L. C., A sensitive field test for heavy metals in water: Econ. Geol., vol. 43, pp. 675–684, 1948.
12. Iuneev, M. V., Possibilities for geophysical prospecting for manganese deposits of the southern Urals (in Russian): Vsesoiuznogo Nauchno-Issledovatel'skogo Geologicheskogo Instituta, Materialy Geofizika, Sb. 12, pp. 103–124, 1948.
13. Kreiter, V. M., Search and prospecting for useful minerals (in Russian): Moscow, Leningrad, pp. 284–290, 1940.
14. Lakin, H. W., Stevens, R. E., and Almond, Hy, Field method for the determination of zinc in soils: Econ. Geol., vol. 44, pp. 296–306, 1949.

15. Leach, Paul, Simple chemical tests to aid prospectors: Eng. and Min. Jour., vol. 148, pp. 78–79, 1947.
16. Lidgey, Ernest, Some indications of ore deposits: Australasian Inst. Min. Eng. Trans., vol. 4, pp. 110–122, 1897.
17. Linstow, O. V., Die natürliche Anreicherung von Metallsalzen und anderen anorganischen Verbindungen in den Pflanzen: Fedde Repert, Beihefte 31, Berlin, 1924.
18. Locke, Augustus, Leached outcrops as guides to copper ore, pp. 81–89, Williams and Wilkins Co., Baltimore, 1926.
19. Lovering, T. S., Organic precipitation of metallic copper: U. S. Geol. Survey Bull. 795, pp. 45–52, 1927.
20. Lovering, T. S., Huff, L. C., and Almond, Hy, Dispersion of copper from the San Manuel copper deposit, Pinal County, Arizona: manuscript in preparation, 1949.
21. Lundberg, Hans, On the history of geophysical exploration: Canadian Inst. Min. Metallurgy Bull., vol. 41, pp. 171–185, 1948.
22. Lungwitz, E. E., Der geologische Zusammenhang von Vegetation and Goldlagerstatten: Zeitschr. prakt. Geologie, vol. 8, pp. 71–74, 1900.
23. Maliuga, D. P., On soils and plants used in the search for metals (in Russian): Akad. Nauk Izv., Ser. Geol., 1947, No. 3, pp. 135–138.
24. Percy, John, Metallurgy, Introduction, refractory materials and fuel, p. 211, John Murray, London, 1875.
25. Rankama, Kalervo, On the use of the trace elements in some problems of practical geology: Comm. géol Finlande Bull. 126, 90 pp., 1940.
26. Rankama Kalervo, Some recent trends in prospecting: chemical, biogeochemical, and geobotanical methods: Mining and Metallurgy, vol. 28, pp. 282–284, 1947.
27. *Ratsbaum, E. A., Field spectroanalytical laboratory for supporting prospecting parties (in Russian): Razvedka Nedr., 1939, No. 1, pp. 38–41, 1939.
28. Reichen, L. E., and Lakin, H. W., Field method for the determination of zinc in plants: U. S. Geol. Survey Circ. 41, 4 pp., 1949.
29. Robinson, W. O., Lakin, H. W., and Reichen, L. A., The zinc content of plants of the Friedensville zinc slime ponds in relation to biogeochemical prospecting: Econ. Geol., vol. 42, pp. 572–582, 1947.
30. Rokhlin, M. I., Experiment in the application of the stanametric survey in the Arctic under permafrost conditions (in Russian): Problemy Arktiki, 1938, No. 4, pp. 61–90, 1938.
31. Sergeev, E. A., Use of spot tests in mineral exploration (in Russian): Razvedka Nedr., 1936, No. 12, pp. 27–29, 1936.
32. *Sergeev, E. A., The physico-chemical method of searching for ores (in Russian): Vsesoiuznogo Nauchno-Issledovatel'skogo Geologicheskogo Instituta, Materialy, Geofizika, No. 9/10, pp. 3–55, 1941.
33. *Sergeev, E. A., Water analysis as a prospecting method (in Russian): Razvedka Nedr., 1946, No. 2, pp. 51–55, 1946.
34. *Sergeev, E., and Solovov, A., Ionic method of geophysical prospecting (in Russian): Materialy, Tsentral'nyi Nauchno-Issledovatel'skii Geologo-Razvedochnyi Institut, Geofizika, No. 3, pp. 1–10, 1937.
35. Short, M. N., Microscopic determination of ore minerals: U. S. Geol. Survey Bull. 914, 1940.
36. Sokoloff, V. P., Geochemical prospecting for ore: Mines Mag., vol. 38, pp. 21–24, 1948.
37. Staker, E. V., and Cummings, R. W., The influence of zinc on the productivity of certain New York peat soils: Soil Sci. Soc. America Proc., vol. 6, p. 207, 1941.
38. Swedish Prospecting Co., P. M. angående vår geokemiska prospekteringsmetod, Malmö, Sweden, 1939.
39. Thyssen, St. V., Geochemische und pflanzenbiologische Zusammenhänge in Lichte der angewandten Geophysik: Beitr. angew Geophysik, vol. 10, pp. 35–84, 1942.
40. *Tikhomirov, N. I., and Miller, S. D., On a physico-chemical method of prospecting for molybdenum in the semi-desert climate of the northern Lake Balkhash area (in Russian): Razvedka Nedr., 1946, No. 2, pp. 34–39, 1946.
41. Vogt, Thorolf, "Kjemisk" og "botanisk" malmletning ved Røros: K. norske vidensk, selsk. Forh., vol. 12, pp. 81–84, 1939.
42. Vogt, Thorolf, and Bergh, H., Bestemmelse av kobber i jordprøver: K. norske vidensk. selsk. Forh., vol. 19, pp. 76–79, 1946.
43. Vogt, Thorolf, and Bergh, H., Sink og bly i jordprøver: K. norske vidensk selsk. Forh., vol. 20, no. 26, pp. 100–105, 1947.
44. Vogt, Thorolf, and Bergh, H., Bestemmelse av jern og mangan i jordprøver: K. norske vidensk. selsk. Forh., vol. 20, no. 27, pp. 106–111, 1947.

* Translations on file in Geological Survey library.

45. Vogt, Thorolf, Braadlie, O., and Berg, H., Bestemmelse Cu, Zn, Pb, Mn og Fe i planter fra Rørosfeltet: K. norske vidensk. selsk. Forh., vol. 16, pp. 55–58, 1943.
46. Vogt, Thorolf, and Bugge, Hans, Bestemmelse av kobber i planter fra Rørosfeltet ved kvantitativ røntgenanalyse: K. norske vidensk. selsk. Forh., vol. 16, pp. 51–54, 1943.
47. Vogt, Thorolf, and Rosenqvist, A. M., Bestemmelse av kobber i vannprøver fra Rørosfeltet: K. norske vidensk. selsk. Forh., vol. 15, pp. 87–90, 1942.
48. Warren, H. V., and Delavault, R. E., Biogeochemical investigations in British Columbia: Geophysics, vol. 13, pp. 609–624, 1948.
49. Warren, H. V., and Delavault, R. E., Further studies in biogeochemistry: Geol. Soc. America Bull., vol. 60, pp. 531–560, 1949.
50. Warren, H. V., and Delavault, R. E., Gold and silver content of some trees and horsetails in British Columbia: Geol. Soc. America Bull., in press, 1949.
51. Warren, H. V., and Howatson, C. H., Biogeochemical prospecting for copper and zinc: Geol. Soc. America. Bull., vol. 58, pp. 803–820, 1947.

BURIED PREGLACIAL GROUND WATER CHANNELS IN THE ALBANY–SCHENECTADY AREA IN NEW YORK.[1]

E. S. SIMPSON.

ABSTRACT.

A map is presented showing contours of the buried preglacial channel of the Mohawk River from Schenectady, New York, to its confluence with the Hudson River about 12 miles south of Albany and of associated buried preglacial channels. The Pleistocene history of a portion of the Mohawk and Hudson Rivers is discussed, and the relation of buried valleys to ground-water supplies is indicated.

INTRODUCTION.

THE United States Geological Survey, in cooperation with the New York State Water Power and Control Commission, is making a general investigation of the ground-water resources of the Upstate areas of New York. The work is being conducted under the general supervision of M. L. Brashears, Jr., district geologist of the Ground Water Branch of the Geological Survey for New York and New England. The writer believes that the well data collected in Albany, Schenectady, and Saratoga Counties are sufficient to justify an attempt at constructing a contour map of the buried bedrock surface which would locate more precisely than heretofore the preglacial course of the lower Mohawk River and of other streams in the immediate vicinity.

The area treated is in the east-central part of New York State, south of the confluence of the Mohawk and Hudson Rivers. It includes the entire Albany quadrangle and the southern third of the Schenectady quadrangle, New York, and includes the cities of Albany and Schenectady.

Within the area treated the Mohawk River flows at an elevation of about 200 feet above sea level. The Hudson is only slightly above sea level and is affected by tides. The land surface north and east of Voorheesville (Fig. 1) is flat or gently rolling except where cut into by streams, and mostly lies at elevations between 200 and 400 feet above sea level. South and west of Voorheesville the land surface is hilly and rises towards the Helderberg escarpment.

All boring data used by the writer in the construction of Figure 1 have been obtained from the files of the U. S. Geological Survey and from records of wash borings published in the Deep Waterways Report of 1900.[2] A part of the records collected by the Geological Survey and used herein were obtained through interviews with well owners, many of whom supplied data

[1] Published with the approval of the Director of the U. S. Geological Survey.

[2] Report of the Board of Engineers on Deep Waterways: House of Rep. Doc. No. 149, G. P. O., 1900.

from memory. Although these records are believed to be essentially accurate, it is obvious that they cannot be guaranteed. The wash borings were driven to refusal and it appears likely that some of them were ended on boulders and not on bedrock.

PLEISTOCENE HISTORY.

It is believed that in pre-Pleistocene time the land area of what is now east-central and southeastern New York State stood at a much higher elevation in relation to sea level than is now the case. The Hudson River and its main tributaries, including the lower part of the Mohawk River, were youthful streams and actively downcutting their channels. Data presented in this paper and elsewhere [3] tend to show these channels to be relatively steep walled and deep enough so as perhaps to deserve to be called gorges. In the Albany-Schenectady area the development of the Hudson and Mohawk gorges may have taken place in two stages and a gorge within a gorge may exist, particularly in the Hudson Valley. The inner gorge, if a distinct and continuous inner gorge actually exists, must be very narrow. These features are shown in Figure 2.

Further development of the Mohawk-Hudson gorge was interrupted by subsidence of the land, which possibly may have coincided with the invasion of the continental ice sheet. After retreat and stagnation of the last ice sheet, the land has undergone uplift, but the magnitude of this uplift in the Albany-Schenectady area is slight in comparison to the magnitude of the preglacial and glacial subsidence. The gorge bottom, which must have been appreciably above sea level in the earlier time, is now several hundred feet below sea level.

Undoubtedly, prior to the time of burial, the Mohawk, Hudson, and other channels of the area must have been affected, to a greater or less degree, by ice erosion. From existing topographic evidence, the general direction of the movement of the last ice sheet in the Albany-Schenectady area seems to have been southerly to southwesterly, the southwesterly trend being more in evidence in the Schenectady section. Thus, the ice motion was more or less parallel to the axes of the Colonie channel and the Hudson channel (Fig. 1), whereas its trend was transverse to the direction of the Mohawk channel. In view of this, it would be expected that the sides of the Colonie and Hudson channels would have been over-steepened and widened by the ice, and that their floors, perhaps, would have been deepened.[4] Possibly the channels assumed the form of typical U-shaped glacial troughs. On the other hand, the Mohawk channel, because it lay athwart the direction of ice advance, would have undergone dissimilar and probably much less ice erosion. Indeed, the now-buried channel walls of the Mohawk seem less steep than those of the Hudson and Colonie (Fig. 1) and the accumulation of bottom till (hardpan) in the Mohawk channel seems to be greater. However, more data must be-

[3] Berkey, C. P., Geology of the New York City (Catskill) aqueduct: New York State Mus. Bull. 146, 1911.

[4] Berkey, C. P., op. cit., p. 95.

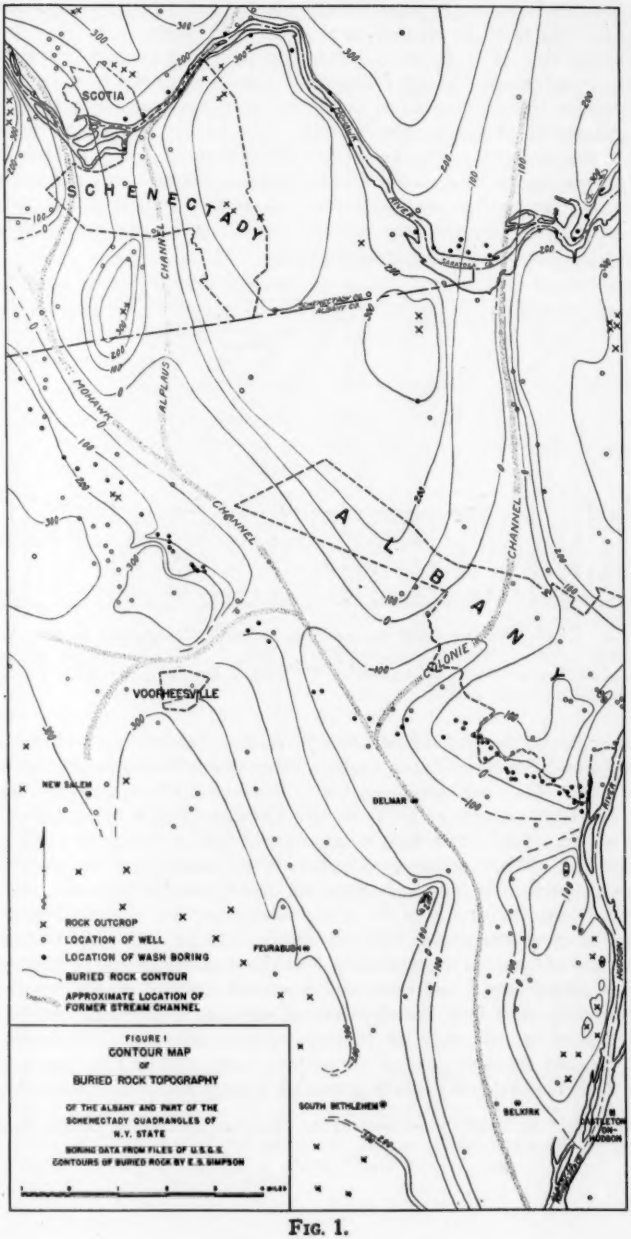

SCOTIA
SCHENECTADY
CHANNEL
MOHAWK
ALPLAUS
CHANNEL
ALBANY
CHANNEL
COLONIE
VOORHEESVILLE
NEW SALEM
DELMAR
FEURABUSH
SOUTH BETHLEHEM
SELKIRK
ROCK OUTCROP
LOCATION OF WELL
LOCATION OF WASH BORING
BURIED ROCK CONTOUR
APPROXIMATE LOCATION OF FORMER STREAM CHANNEL
FIGURE I
CONTOUR MAP
OF
BURIED ROCK TOPOGRAPHY
OF THE ALBANY AND PART OF THE SCHENECTADY QUADRANGLES OF N.Y. STATE
BORING DATA FROM FILES OF U.S.G.S.
CONTOURS OF BURIED ROCK BY E.S. SIMPSON

FIG. 1.

come available before it is possible to make statements with confidence concerning the effects of ice erosion on the buried channels.

Although there was probably more than one advance and retreat of the ice front over the area during Pleistocene time, it is to the final ice sheet of the Wisconsin stage that most of the débris now found mantling the bedrock in the Albany-Schenectady area is attributed. In the opinion of the writer the till in the Mohawk channel must have been derived almost entirely, if not entirely, from the ice sheet of the Wisconsin stage, because only one till, which lies directly over bedrock, has been observed in the area. Till was deposited almost everywhere in this area under the moving ice sheet and in places reached a thickness of about a hundred feet.

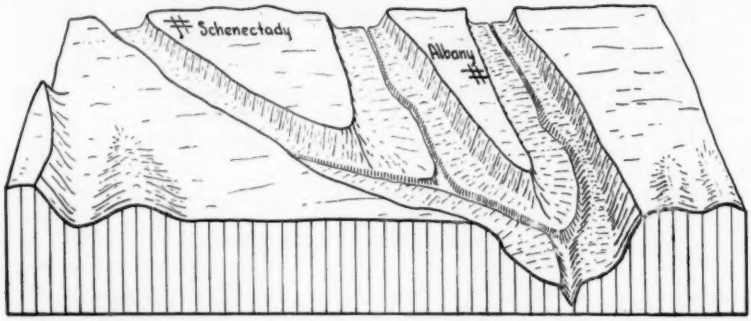


FIG. 2. Block diagram showing possible bedrock topography in the Albany-Schenectady area (Diagram modified after Cook, J. H., Chapter on glacial geology, *in* Geology of the Capital District, by Rudolf Ruedemann; New York State Mus. Bull. 285, p. 188, 1930).

During part of the final stagnation of Wisconsin ice, there existed over much of the Albany-Schenectady area a glacial lake which Woodworth[5] has called Lake Albany. The approximate outline of this lake in the Albany-Schenectady area is shown on the map (Fig. 1) by the 300-foot contour line. Glacial outwash was deposited in this lake, a large part of it as deltas of varying size and character. Much of these sediments were transported to the Albany-Schenectady part of the lake from the west, and especially large amounts were deposited during the time that the Mohawk drained the glacial Great Lakes.

The history of deposition was not simple. In general (and without attempting any correlation), considering first the deposits in the Mohawk channel, cross-bedded gravel and sand was deposited upon till in the Scotia area, sands were deposited over the clay and till west of Albany, and chiefly clays were deposited on till south of Albany. The northward extension of the Colonie channel probably carried outwash to Lake Albany from areas to the north. This outwash very likely provided a large portion of the fill which

[5] Woodworth, J. B., Ancient water levels of the Champlain and Hudson Valleys: New York State Mus. Bull. 84, p. 175, 1905.

now occupies the Colonie channel between Albany and the present-day Mohawk River. This fill is much more irregular than that which occupies the Mohawk channel. It is coarsest to the north; to the south, in the vicinity of Albany, it consists chiefly of clay. A deposit of gravel, in places about 60 feet thick, is found in and near the villages of Voorheesville and New Salem.

From these and other sources, material was washed into Lake Albany in sufficient quantity to obliterate all, or nearly all, of the preglacial drainage pattern below about the 300-foot contour in the Schenectady-Albany area.

When Lake Albany was drained the Mohawk River downstream from Schenectady failed to reoccupy its old channel. Instead, it zigzagged eastward, cutting a new channel in part through glacial débris and in part through consolidated rock. Where the channel is in glacial débris the river is relatively wide and its banks have gentle slopes, but where the channel lies in rock the river is narrow and the walls often precipitous.

THE BURIED CHANNELS.

Of the buried channels shown on Figure 1, three are fairly well substantiated by available data. These are here named the Mohawk channel, the Alplaus channel, and the Colonie channel. The existence of each of these channels has been recognized heretofore[6] but their locations have remained vague and unknown. Cook[7] believed the buried Mohawk channel to join the Hudson near Albany instead of about 12 miles south of Albany, as believed by the writer. The well records also suggest the existence of two other channels which have not been named. Evidence of their existence is presented here for the first time. One joins the Mohawk channel southwest of Schenectady and the other joins the Mohawk channel northeast of Voorheesville.

The buried channel of the Mohawk continues upstream from Schenectady (and off the map) for about 8 miles to Hoffmans, New York. The channel fill in this reach is about 200 feet thick and the existing Mohawk River meanders over its surface. At Hoffmans the Hoffmans fault intersects the river and in preglacial time was probably the site of a waterfall about 100 feet high. Where it crosses the river, the west, upthrown side of the fault is capped by beds of relatively resistant Little Falls dolomite of Upper Cambrian age. The downthrown side consists largely of weak shales of the Middle Ordovician Schenectady formation. The average gradient of the buried Mohawk channel from Hoffmans to its confluence with the Colonie channel is probably about 8 or 9 feet per mile.

There is evidence based on a study of well logs that an inner notch exists in the buried Mohawk channel from Hoffmans to its confluence with the present Hudson River somewhere south of Selkirk. The elevation of bedrock at, and downstream from, the confluence of the Mohawk and Colonie channels is shown to be about 100 feet below sea level (Fig. 1). However, at this

[6] Cook, J. H., Some preglacial valleys in eastern New York and their relation to existing drainage (abst.): Science, new ser., vol. 29, p. 750, 1909.
Stoller, J. H., Glacial geology of the Schenectady quadrangle: New York State Mus. Bull. 154, p. 12, 1911.

[7] Cook, J. H., Chapter on glacial geology, *in* Geology of the Capital District, by Rudolf Ruedemann: New York State Mus. Bull. 285, p. 188, 1930.

elevation the channel probably is part of the inner notch mentioned, and must be relatively narrow. Because boring data are insufficient to locate it precisely, the —100 foot contour is drawn to show the entire range of possible positions that the inner notch might occupy.

The northward extension of the Colonie channel is believed by Stoller [8] to have included a rock depression now occupied in part by Round Lake and by Saratoga Lake. The continuation of this channel northward of Saratoga Lake is obscure, but it is possible that it reached northward and westward to drain part of the southeast slope of the Adirondack Mountains. The part of the channel shown on Figure 1 seems relatively steep walled and suggests a typical glacial trough.

At the north end of Saratoga Lake, about 12 miles north of the northern boundary of Figure 1, a well boring shows bedrock to be at about 45 feet above sea level. Unless the bedrock at this location was locally overdeepened by ice erosion, this boring suggests the existence of a continuous buried stream channel from the north end of Saratoga Lake to a confluence with the buried Mohawk channel south of Albany, its average gradient between these places approximating 6 feet per mile. Thus the Colonie channel may have carried the master stream of the area in preglacial time, since this gradient seems flatter than any of the others, including, perhaps, the gradient of the buried channel occupied by the present Hudson River in the Albany area. Indeed, the boring mentioned and the topography north of Albany suggest that the buried channel under the Hudson at Albany formerly drained the Hoosic and Batten Kill watersheds (as is now the case), but did not extend much north of Batten Kill, and that the Lake Champlain and Lake George watersheds were drained by southward-flowing streams that intersected the existing Hudson near Fort Edward and west of Glens Falls, respectively, and may have continued on to the buried valley the writer has named the Colonie channel.

The Alplaus channel is much smaller than the Colonie and Mohawk channels, and consequently its pre-Pleistocene watershed was probably of relatively limited extent. Stoller [9] believes that the northward extension of the Alplaus channel included what is now Ballston Lake, and also that it branched off westward to drain part of Glenville Hill. Its average gradient seems to be about 15 feet per mile for the portion contoured.

In the Albany area the available data are insufficient to indicate the depth of fill under the existing Hudson River. In the downtown business section of the city of Albany, about 1,000 feet west of the river, borings show bedrock to be about 50 feet below sea level, and in the city of Rensselaer, on the east bank of the river opposite Albany, borings show bedrock to be about at sea level or higher. Inasmuch as borings in the buried Mohawk-Colonie channel, about 5 miles upstream from its confluence with the existing Hudson River and about 7 miles south of Albany, show bedrock at 190 feet below sea level, we are faced with the following possibilities:

[8] Op. cit., p. 12.
[9] Op. cit., p. 12.

(1) Bedrock under that portion of the existing Hudson River shown on Figure 1 is also about 190 feet below sea level.

(2) The buried Mohawk-Colonie channel was overdeepened by ice erosion which did not affect the buried Hudson channel to an equal degree.

(3) The preglacial stream that occupied the buried channel over which the existing Hudson now flows in the vicinity of Albany had a smaller flow (less erosive power) upstream from its confluence with the preglacial Mohawk, than did the preglacial Mohawk.

Present-day records of stream flow [10] show that the average discharge of the Hudson River at Mechanicville (about 20 miles upstream from Albany and about 10 miles upstream from its confluence with the existing Mohawk River) is about 7,400 cubic feet per second, whereas the average discharge of the Mohawk River at Cohoes (which is near its confluence with the Hudson) is about 5,600 cubic feet per second. Thus the present-day Hudson is clearly the larger stream.

A study of the existing topography of east-central and northeastern New York makes it evident that, in preglacial time, a large master stream existed which drained a basin as large, if not larger, than that drained by the present-day Hudson above its confluence with the Mohawk River. This preglacial stream must have flowed southward near what is now Albany. Thus it may well be that the preglacial Hudson occupied a different channel in the vicinity of Albany than is now the case. Perhaps this channel was the Colonie channel as shown on Figure 1. A further study of existing data and the accumulation of new data may be necessary to decide the issue.

GROUND-WATER SUPPLIES FROM BURIED VALLEYS.

The location and mapping of buried channels, such as presented in this paper, have economic as well as academic interest. Perhaps the aspect of the problem of greatest economic importance is the relation of buried channels to the occurrence of ground water. Glacial outwash, filling the rock channels of rivers, in many places provides the source from which tens of millions of gallons of water may be pumped daily.

In the area shown on Figure 1, the most favorable opportunity for obtaining large supplies of ground water lies in the Pleistocene gravel delta deposit that partly fills the Mohawk channel south and west of Scotia. The withdrawal from these gravels is, at present, in excess of 20 million gallons a day, and it is likely that the ground-water pumpage will be nearly doubled in the near future, owing to increased industrial use by plants presently under construction, and to wider domestic use through the contemplated formation of new municipal water systems. Available data show that the downstream periphery of this delta is sharply delineated, and that the municipal supply wells of the city of Schenectady, which account for most of the pumpage from this well field, are within 1,500 feet of the periphery.

[10] U. S. Geol. Survey Water Supply Paper 1031, Surface water supply of the United States, pt. 1, pp. 255, 276, 1945.

The Colonie channel, athough a less favorable area for the development of ground-water supplies than the Mohawk channel near Scotia, nevertheless provides in excess of 2 million gallons a day for the Latham Water District of the town of Colonie. There are also several hundred domestic and industrial wells deriving their supply from outwash in the Colonie channel.

A small public water-supply system obtains ground water from wells penetrating the gravels near New Salem, and several industrial wells in and near Voorheesville penetrate what may be the same gravel deposit.

The sands underlying the plain that forms the land surface over much of the area of glacial Lake Albany are tapped by several thousand shallow domestic wells. Unfortunately, in many places this sand is of insufficient thickness to provide a dependable water supply in late summer and early fall. In addition, hundreds of domestic wells and a number of industrial wells scattered over the remainder of the area depend on glacial drift of different types for their entire supply.

Except for a relatively small area shown in the southwestern part of Figure 1, where the Manlius limestone of Silurian age and several limestones of Devonian age are found, there is no bedrock aquifer capable of yielding more than about 10 gallons of potable water per minute to any well, no matter how deep. Future ground-water development in the highly populated and industrialized Albany-Schenectady area must therefore continue to depend on glacial outwash for its source of supply.

The trend toward increased consumption of ground water for industrial and other uses is evident in the Albany-Schenectady area, as elsewhere. The supply is large but in no case is it unlimited, and there can be little doubt that all possible sources will receive closer study as time goes by. Many buried channels in New York and New England, such as those described in this paper, are capable of yielding large and convenient supplies of ground water, and, therefore, deserve continued and close study on the part of water-supply geologists and engineers.

U. S. Geological Survey,
Albany, N. Y.,
July 8, 1949.

TRANSPORT AND DEPOSITION OF THE NON-SULPHIDE VEIN MINERALS. V. ZIRCONIUM MINERALS.[1]

O. D. MAURICE.

ABSTRACT.

The synthesis and stability of zirconium minerals was studied in aqueous solutions at a temperature of 400° C and at a pressure of 900 atmospheres. The compositional fields of stability of the minerals zircon and baddeleyite are outlined approximately. Zircon has a wide field of stability in acid solutions but its field of stability in alkaline solutions is restricted by limits close to the neutral point. Baddeleyite has a restricted field in acid solutions and a very wide one in alkaline solutions. At least 4 zircono-silicates were obtained as products; three of these have not been described in the literature. Solubility tests showed that zirconium compounds are insoluble in alkaline solutions but are very soluble in dilute HCl solutions. From these tests and from the other experimental data some geological conclusions are drawn regarding the occurrence of zirconium minerals and the nature of the solutions which transported the element.

INTRODUCTION.

VERY little is known about the synthesis and stability of zirconium minerals in aqueous solutions. Zircon has been synthesized repeatedly by Sainte-Claire Deville (4),[2] P. Hautefeuille (6) and K. Chrustschoff (2), but although some of the laboratory processes are related to the possible natural processes of deposition of the mineral to a certain extent, they invariably required temperatures approaching redness with water either absent or present in small amounts. In the present series of experiments, zircon was synthesized at 400° C in aqueous solutions.

The following experiments are part of a program of research initiated at the University of Toronto to test the possibility or impossibility of the alkaline theory of ore deposition. In outlining this program, F. G. Smith (9) pointed out a number of questions which must be answered before the theory can be accepted as possible or not. One of these questions is as follows: "Are all of the non-sulphide minerals stable in, and can they be crystallised from alkaline solutions." In the present paper the author proposes to answer this question in part by outlining the limits of stability of some zirconium minerals in alkaline and acid solutions at a temperature of 400° C and at a pressure of about 900 atmospheres.

[1] This is a condensation of part of a thesis submitted to the University of Toronto in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

[2] Numbers in parentheses refer to Bibliography at end of paper.

EXPERIMENTAL METHOD.

The steel pressure bomb used for heating the charges of these experiments has been described by F. G. Smith (10). The internal graphite crucible had a capacity of 80 cc; it was 75 percent filled with water or water solutions in all of the experiments. In addition to water, the charge consisted of varying proportions of ZrO_2 and SiO_2, the total weight of these constituents being 0.02 Molar. The *p*H of the solution was varied from slightly acid to strongly alkaline, using HCl and NaOH.

The bomb containing the charge was brought to a temperature of 400° C in about 4 hours. It was kept at this temperature for about 70 hours. It was then removed from the furnace and chilled in air. The solution in the bomb was tested qualitatively for zirconium by a microchemical test and the solid products were washed several times with distilled water and dried before microscopical examination.

In testing the solution in the bomb for zirconium, the method recommended by Biltz and Mecklenburg (1) was found very useful, since zirconium is detected even when the solution contains as little as 0.0005 percent of zirconia. The test consists of making the solution strongly acid with hydrochloric acid. The solution is warmed and a few drops of sodium phosphate are added. A white gelatinous precipitate indicates the presence of zirconium in the solution.

The solid products of each run of the bomb were examined under the microscope and the indices of refraction were determined by immersion in oils. No attempt has been made to identify all of the products obtained. Some compounds already described in the literature were recognized and some had optical properties different from any recorded compound. In a few cases X-ray powder pictures were made to ascertain the identity of zircon and baddeleyite by comparison with natural minerals.

CHEMICALS.

Sodium hydroxide, C.P. Pellets (Baker's).
Acid silicic, C.P. Powder (Baker's).
Hydrochloric acid, C.P.

$ZrO(OH)_2$. This material was prepared by dissolving ZrO_2, C.P. Powder (Fisher) in boiling hydrofluoric acid and evaporating the solution to dryness. The resulting crystals of ZrF_4 were dissolved in water and $Zr(OH)_4$ was precipitated with NH_4OH. The precipitate was washed several times with concentrated NH_4OH. After drying the precipitate at 110° C the resulting salt was $ZrO(OH)_2$. It contained approximately 2.5 per cent F.

EXPERIMENTAL RESULTS.

A list of the experiments carried out during this investigation is given in Table 1. The last column shows the resulting products. Experiment No. 1 did not give a resolvable product because it was conducted at a lower temperature (300 ° C) and during a shorter time (40 hours). In Figure 1, the

TABLE 1.

Exp. no.	Wt. $ZrO(OH)_2$ grs.	Mols. ZrO_2 a	Wt. silicic acid grs.	Mols. SiO_2 b	Mol. % ZrO_2 $\frac{100a}{a+b}$ %	Mol. % SiO_2 $\frac{100b}{a+b}$ %	Normality		Solid products
							$xNNa_2O$	$yNHCl$	
1	0.4803	0.00034	0.3715	0.00046	42.5	57.5	Neutral		No apparent reaction
2	1.3272	0.00094	0.4648	0.00057	62.1	37.9	0.06		Zircon and baddeleyite
3	1.3272	0.00094	0.4658	0.00063	59.6	40.4	0.30		Baddeleyite and $Na_2O.ZrO_2$, $1.5SiO_2$
4	1.4374	0.00102	0.8030	0.00099	50.7	49.3	0.62		Baddeleyite, $Na_2O.ZrO_2.1.5SiO_2$ and Phase I
5	1.4374	0.00102	0.8030	0.00099	50.7	49.3	1.26		Baddeleyite and $Na_2O.ZrO_2.1.5SiO_2$
6	1.4374	0.00102	0.8030	0.00099	50.7	49.3	2.59		Baddeleyite, $Na_2O.ZrO_2.1.5SiO_2$ and Phase I
7	0.7187	0.00051	1.2045	0.00148	25.6	74.4	1.26		Phase I and Phase K
8	2.1560	0.00153	0.4015	0.00049	75.8	24.2	1.22		Baddeleyite and $Na_2O.ZrO_2.1.5SiO_2$
9	2.5871	0.00184	0.1606	0.00020	90.2	9.8	1.22		Baddeleyite and $Na_2O.ZrO_2.1.5SiO_2$
10	2.8748	0.00205	0.00	0.00	100.0	0.0	1.22		Baddeleyite
11	2.1560	0.00153	0.4015	0.00049	75.8	24.2	0.65		Baddeleyite, $Na_2O.ZrO_2.1.5SiO_2$ and Phase G
12	1.4374	0.00102	0.8030	0.00099	50.7	49.3		0.65	Zircon
13	0.7187	0.00051	1.0045	0.00148	25.6	74.4	0.62		Phase I and Phase K
14	2.1560	0.00153	0.4015	0.00049	75.8	24.2		0.65	Zircon
15	2.5871	0.00184	0.1606	0.00020	90.2	9.8	0.65		Baddeleyite, $Na_2O.ZrO_2.1.5SiO_2$ and Phase G
16	1.4374	0.00102	0.8030	0.00099	50.7	49.3		0.33	Zircon
17	0.7187	0.00051	1.2045	0.00148	25.6	74.4	0.31		Phase I and Phase K
18	0.2874	0.00020	1.4454	0.00178	10.1	89.9	0.65		Phase I and Phase K
19	2.1560	0.00153	0.4015	0.00049	75.8	24.2	2.59		Baddeleyite and $Na_2O.ZrO_2.1.5SiO_2$
20	1.4374	0.00102	0.8030	0.00099	50.7	49.3	4.05		Baddeleyite, $Na_2O.ZrO_2.1.5SiO_2$ and Phase I
21	0.7187	0.00051	1.2045	0.00148	25.6	74.4	4.00		Phase I and Phase K
22	0.7187	0.00051	1.1580	0.00148	25.6	74.4	0.08		Phase I and Phase K
23	0.7187	0.00051	1.1580	0.00148	25.6	74.4	Neutral		Quartz and Zircon
24	2.8748	0.00205	0.00	0.00	100.0	0.0	Neutral		Baddeleyite
25	1.2361	0.00089	0.8800	0.00114	43.7	56.3	0.06		Zircon and Phase I
26	0.1723	0.00012	1.4512	0.00189	6.0	94.0	0.06		Quartz and Phase I
27	1.2361	0.00089	0.8800	0.00114	43.7	56.3	0.51		$Na_2O.ZrO_2.1.5SiO_2$ and Phase I
28	2.1560	0.00153	0.3860	0.00049	75.8	24.2	0.15		Baddeleyite and Zircon
29	2.6928	0.00190	0.0977	0.00013	93.5	6.5	4.02		Baddeleyite and $Na_2O.ZrO_2.1.5SiO_2$
30	2.1560	0.00153	0.3860	0.00049	75.8	24.2	0.22		Baddeleyite, $Na_2O.ZrO_2.1.5SiO_2$ and Phase G

ratio of ZrO_2 to SiO_2 is plotted against the alkalinity of the solution. In Figure 2, the scale is enlarged somewhat near the neutral point and is also extended into the acid side of neutrality. The fields of stability of quartz, zircon, baddeleyite and zircono-silicates are outlined approximately in Figures 1 and 2. Further experiments would delimit the fields more accurately, but the positions are defined sufficiently for the purpose of this series of experiments.

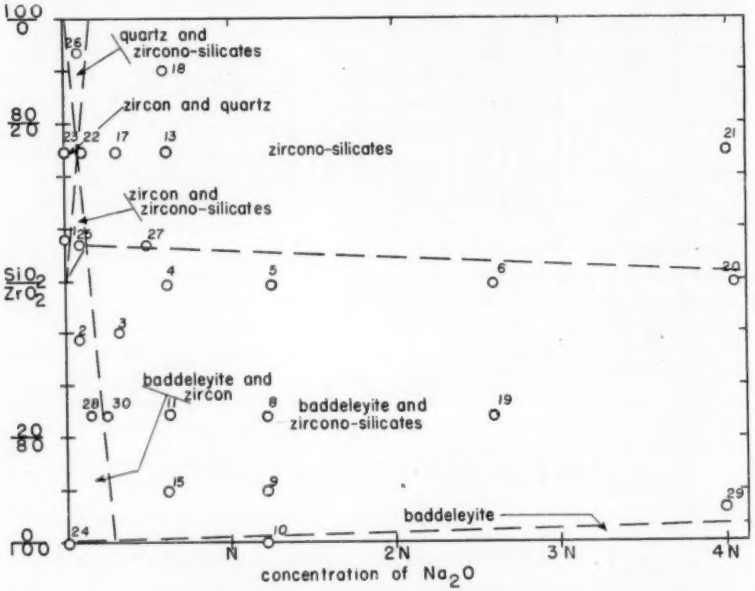


FIG. 1. Approximate phase relations in the system ZrO_2-SiO_2-Na_2O in water at 400° C. The non-variant conditions are explained in the test.

The problem of distinguishing the minerals zircon and baddeleyite among the end products was a simple one. Both minerals have indices of refraction above 1.9, but zircon occurred in the products as minute equi-dimensional and colorless crystals, while baddeleyite had a pale yellow color and occurred as irregular translucent aggregates. The chemical behavior of the two minerals in dilute hydrochloric acid is also useful in distinguishing them; zircon is insoluble, while baddeleyite is soluble.

In a few cases, X-ray powder diffraction photographs were taken of the synthetic products and the spacings were compared with those of natural zircon and baddeleyite. The identity of the minerals was confirmed. The X-ray photographs are compared in Figure 3. The products of run No. 12 contained zircon as the only stable solid phase (Figure 3-b). The extra lines

in Figure 3-c are due to the presence of baddeleyite among the products of run No. 2.

Quartz was also readily recognized because it has such a low index of refraction as compared with most of the products obtained. In many cases, the crystals were sufficiently well developed so that some of the characteristic forms could be recognized.

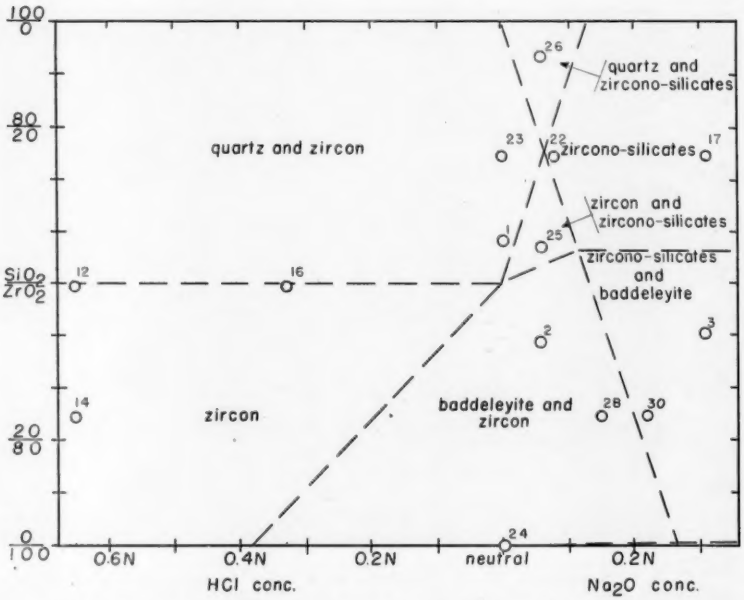


FIG. 2. Approximate phase relations in the system ZrO_2-SiO_2 in dilute solutions of HCl and Na_2O at 400° C. The non-variant conditions are explained in the text.

The compound $Na_2O.ZrO_2.1.5SiO_2$ described by J. D'Ans and J. Loffler (3) was recognized among the experimental products. It is uniaxial negative, and the crystals are often well developed with rhombohedral habit. The specific gravity determined with the pyknometer is 2.88. The indices of refraction are $\epsilon = 1.692$, $\omega = 1.715$.

In addition to the above mentioned compound, three other zirconosilicates were observed among the products (Phase G, I, and K). No zirconium compounds with similar optical properties have as yet been described in the literature. The crystals of phase G have a tabular habit and form beautiful pseudo-hexagonal twins. Their index of refraction varies from $n_p = 1.702$ to $n_g = 1.712$. Phase I is a hydrate; its crystals form long slender needles with nearly parallel extinction and arranged in radiating groups. The

field of stability of Phase I is broad, having been observed in the low as well as in the high alkali runs. The indices of refraction were not constant over the whole range of stability, indicating possible isomorphous substitution of H^+ for Na^+ in their structure. The lowest measured index of refraction of these crystals is 1.615 in the low alkali runs. The index increases gradually with increase of alkalinity, so that in Experiment No. 20, the highest index

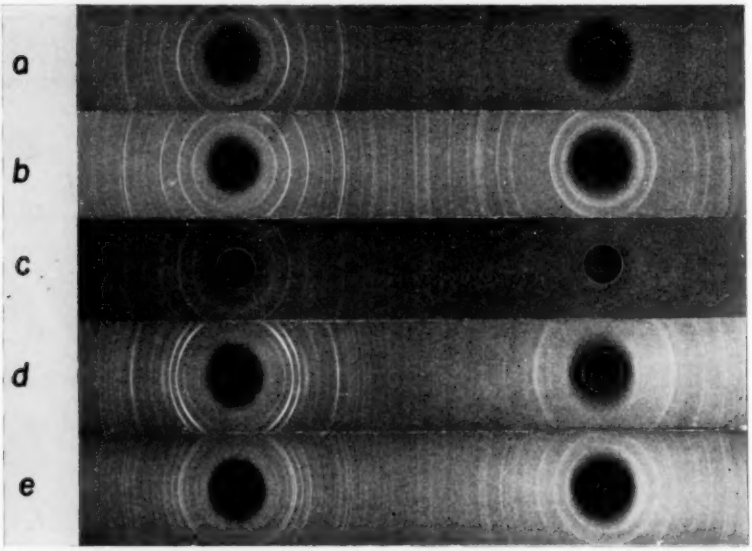


FIG. 3. Comparative X-ray diffraction patterns of natural and artificial zirconium minerals. (a) Natural zircon (unknown locality). (b) Artificial zircon produced in run No. 12. (c) Artificial zircon produced in run No. 2; the extra faint lines are due to the presence of baddeleyite. (d) Natural baddeleyite from Minas Geraes, Brazil. (e) Artificial baddeleyite produced in run No. 10.

was 1.715. The birefringence of this phase is of the order of 0.02. Phase K is always associated with Phase I in the high silica runs. Its crystals are tabular, with a square cross section and a symmetrical extinction. The index of refraction of Phase K varied with the difference in alkalinity of the solution and like phase I, they are believed to be hydrates. Isomorphous substitution of H^+ for Na^+ may be responsible for the variation of the index of refraction. The lowest measured indices were in the alkali runs of low concentration, where $n_p = 1.540$ and $n_g = 1.550$. In the high alkali run No. 21, the indices were $n_p = 1.605$ and $n_g = 1.610$.

Sodium zirconates and sodium silicates were not expected among the products because they are not stable in dilute solutions. The conditions of temperature and pressure of the experiments were apparently not suitable for

the formation of elpidite ($H_2Na_2Zr(Si_3O_8).H_2O$) and natron-catapleite ($Na_2ZrSi_3O_9.2H_2O$). These minerals are possibly formed at low temperatures in nature.

DISCUSSION OF THE RESULTS.

The System ZrO_2-SiO_2-H_2O.—The anhydrous system ZrO_2-SiO_2 has been described by Washburn (13). A mixture of the two components in equimolar proportion gives a compound $ZrSiO_4$ which melts at 2500° C. When the component water is present, as in the above experiments, the equilibrium is not changed at 400° C and only 3 solid phases are possible as end products, namely SiO_2, ZrO_2, and $ZrSiO_4$. Only two of these phases can exist together at equilibrium.

When a mixture of ZrO_2 and SiO_2 in equimolar proportion is heated with water at 400° C, a pure crop of zircon crystals is obtained because there is little difference in solubility between the components ZrO_2 and SiO_2 in neutral solutions. With a greater mole proportion of silica, only zircon and quartz are stable in neutral solutions. In experiment No. 23 quartz and zircon were produced in about equal proportion.

Experiment No. 1 proved that either or both of ZrO_2 and SiO_2 are not very soluble in water at 300° C, since no evident crystals were produced in this run.

The System ZrO_2-Na_2O-H_2O.—Only one compound can result from mixing the components ZrO_2 and Na_2O: the sodium zirconate Na_2ZrO_3. In water this compound is not stable because it gives all of its alkali to water, leaving ZrO_2 undissolved. Experiment No. 10 proved conclusively that baddeleyite was the only end product obtained when zirconyl hydroxide and sodium hydroxide are heated together in a water solution at 400° C.

Very well developed crystals of Na_2ZrO_3 were obtained by D'Ans and Loffler (3). It is essential for their development that no water be present.

The System SiO_2-Na_2O-H_2O.—Many sodium silicates have been prepared by Morey and Fenner (8) and other investigators working on the anhydrous system SiO_2-Na_2O. Morey has worked on the three component system SiO_2-Na_2O-H_2O and he prepared at least four hydrated sodium silicates. These salts are described by Winchell (14).

The ratio of water to the other two components was always very high in the experiments, so that sodium silicates and the hydrated salts were not stable in such solutions. The solutions could be saturated with quartz only when the alkalinity was low, because the mineral is quite soluble in alkaline solutions. No bomb runs were made in the system SiO_2-Na_2O-H_2O; the field of quartz was outlined approximately by experiments No. 22 and 26. From Figure 2, it is seen that solutions of higher alkalinity than 0.15N Na_2O would be unsaturated with 0.02 moles of silica.

The System ZrO_2-HCl-H_2O.—Zirconium tetrachloride ($ZrCl_4$) is not stable in aqueous solutions and even the humidity of the atmosphere decomposes this salt to the zirconyl chloride ($ZrOCl_2$) and hydrochloric acid is given off. When zirconyl chloride crystallises it combines with water of crystallisation giving the hydrated salt $ZrOCl_2.8H_2O$. These crystals separate

out from a concentrated solution of HCl but are quite soluble in a dilute HCl solution.

Baddeleyite is stable in a very dilute solution of HCl when there are not enough Cl^- ions to react with the ZrO^{++} radical. In this case the reaction:

$$ZrO_2 + 2HCl = ZrOCl_2 + H_2O,$$

is not complete and the dioxide can be in equilibrium in the solution. As a result of the above experiments it was calculated that the reaction is complete at equilibrium in 0.381 N HCl solutions.

The System SiO_2-HCl-H_2O.—SiO_2 is only slightly soluble in neutral solutions and the solubility decreases with increasing concentrations of HCl according to Lenher and Merril (7). In dilute HCl solutions the tetrachloride ($SiCl_4$) is not stable so that silica is expected as the only solid product when it is heated in a dilute hydrochloric acid solution.

Field of Stability of Zircon.—The experiments proved that zircon has a very limited field of stability in alkaline solutions and a very broad one in acid solutions. Only three runs were made in dilute hydrochloric acid and all contained zircon as the only stable solid phase. The concentration of ZrO_2 in run No. 14 was greater than equimolar with respect to SiO_2, but owing to the formation of the zirconyl chloride ($ZrOCl_2$) and its great solubility in dilute HCl, the only solid phase remaining was the silicate.

The field of zircon on the acid side of the diagram (Fig. 2) is not believed to be restricted by any lines except those representing 100 percent ZrO_2 and 100 percent SiO_2 concentrations. If the two constituents ZrO_2 and SiO_2 are in the presence of each other in dilute acid solutions, the silicate will form and will be stable. Zircon is the only solid phase possible when the ratio of ZrO_2 to SiO_2 is greater than 1 and when the normality of the solution is great enough to complete the transformation of the dioxide to the oxychloride of zirconium. Quartz and zircon will exist together if the ratio of $ZrO_2 : SiO_2$ is smaller than 1.

In alkaline solutions, it is not possible to obtain a pure crop of zircon crystals; the zircon may be stable with baddeleyite even when the $ZrO_2 : SiO_2$ ratio is less than 1 because silica is soluble in alkaline solutions and the dioxide of zirconium is not. The field of zircon on the alkaline side was delimited by experiments Nos. 22, 25, 28, and 30.

When the ratio $ZrO_2 : SiO_2$ is less than 1 and when the alkalinity is very low, zircon and quartz can exist together in equilibrium. This field reaches a maximum width for a ratio of ZrO_2 SiO_2 equal to about 1:3. The maximum alkalinity at which quartz and zircon are stable together does not exceed 0.07 N solution of Na_2O.

Experiment No. 25 was made within the field of zircon and zircono-silicates. Neither quartz nor baddeleyite was stable. The zircono-silicate was phase I described above.

Field of Stability of Baddeleyite.—Baddeleyite is in equilibrium with zircon in dilute hydrochloric acid solutions. As was previously mentioned, the normality of the solution must be low enough to prevent complete reaction of

the dioxide with the acid to form the oxychloride which is soluble. Baddeleyite is not stable in solutions of greater HCl normality than 0.381. The field of baddeleyite decreases proportionately with decreasing amounts of free ZrO_2 in the solution.

In alkaline solutions the field of baddeleyite is very broad. It is the only phase possible when there is no silica available for reaction. Baddeleyite is stable alone even when silica is present in small amount, since the silica is taken up in solution and none is left to react with the dioxide. Experiment No. 29 proved, however, that the field in which baddeleyite is stable alone is very restricted. Small amounts of silica in the charge will react to produce the zircono-silicate $Na_2O.ZrO_2.1.5SiO_2$.

A series of bomb runs was carried out with a ratio of $ZrO_2 : SiO_2$ equal to 1, and varying the alkalinity (see experiments Nos. 4, 5, 6, 20). The products of run No. 4 contained approximately 40 percent of baddeleyite while the high alkali run No. 20 contained only 10 percent of the mineral. These experiments helped to delineate the upper boundary of the baddeleyite field. The two runs Nos. 25 and 27 proved that baddeleyite was not stable when the ratio $ZrO_2 : SiO_2$ is smaller than 0.89:1.

Within the field of stability of baddeleyite many zircon-silicates of unknown composition are in equilibrium. Phase G seems to require lower alkalinity than 0.6 N for its formation.

Field of Stability of Quartz.—Quartz is very stable in acid solutions and its solubility decreases with decreasing *p*H values. When the ratio $ZrO_2 : SiO_2$ is smaller than 1, quartz is believed to be stable with zircon and no other phase is possible when the solution is dilute.

Quartz is also produced when the ratio $ZrO_2 : SiO_2$ is slightly greater than 1 in acid solutions, since part of the zirconium dioxide goes into solution. It was not observed in runs Nos. 12 and 16 although the solution contained zirconium. The mineral might have been present in traces, so that the field of quartz may extend slightly lower than the 1:1 ratio line, but this extension is not appreciable in dilute hydrochloric acid solutions.

A few experiments were made to delimit the field of stability of quartz in alkaline solutions. It is evident from Figures 1 and 2 that this field is very restricted. The products of experiment No. 22 did not contain any quartz and those of experiment No. 26 contained quartz in equilibrium with a zircono-silicate.

GEOLOGICAL CONSIDERATIONS.

Zirconium minerals are typically pegmatitic minerals, and apparently have not been found in true hydrothermal veins. This is generally true also of the minerals of the other amphoteric elements. The experimental solubility data have proved that zirconium compounds are insoluble in alkaline solutions but are very soluble in dilute HCl solutions. It seems likely from these experiments that zirconium minerals would be found in hydrothermal veins if the solutions forming the veins were acid. On the other hand, if these solutions are alkaline, they would not be a good medium of transport of zirconium and

this would explain the absence of zirconium minerals in true hydrothermal veins.

Pegmatite dikes in which zirconium minerals are characteristic, are generally held to be due to the crystallization of water-rich silicate melts. Zirconium is soluble in silicate melts as may be demonstrated by a simple experiment. A mixture of average granitic composition was prepared and heated for three hours at 1350° C. It contained 0.3 percent of zirconium, an amount ten times greater than the average content of zirconium in granitic rocks. The resulting glass was clear and did not contain any crystals. It was then concluded that 0.3 percent of zirconium in a silicate melt represents an undersaturation and that this method of transport of the minerals into the pegmatites is both possible and logical.

In another experiment by F. G. Smith (11), 0.62 percent of ZrO_2 was added to a mixture representing the possible composition of the residual liquid after 90 percent crystallization of a granite magma. After heating at $440 \pm 5°$ C for 12 hours and chilling, no trace of zirconium could be found in the water solution standing over the glass.

Zircon is readily crystallized in acid solutions but its field of stability in alkaline solutions is very restricted. The above experiments have proved that zircon is not formed in a solution of greater Na_2O concentration than 0.2 N. However, the natural conditions during the deposition of zircon must be similar to such conditions for other minerals associated with it in igneous rocks and pegmatites, such as the feldspars. Gruner (5) has proved that potash feldspar is not stable in acid solutions but that it is stable in alkaline solutions of limited *p*H. Some of the limiting conditions of the stability of albite have been determined by Smith (12). At 400° C albite is only stable in alkaline solutions with a *p*H over 8.5. It would seem then that zircon and its associated minerals require alkaline conditions for their formation in nature, but that the solutions are not strongly alkaline. This is similar to the conclusions regarding the conditions of formation of tourmaline in nature (12).

ACKNOWLEDGMENTS.

I wish to thank Dr. F. G. Smith for assistance with the phase studies, and Mr. A. R. Graham and Mr. S. A. Forman for the X-ray diffraction patterns. The Advisory Committee on Scientific Research of the University of Toronto provided money for laboratory equipment.

DEPARTMENT OF GEOLOGICAL SCIENCES,
UNIVERSITY OF TORONTO,
TORONTO, CANADA,
July 7, 1949.

BIBLIOGRAPHY.

1. Biltz, W. and Mecklendburg, Z., Qualitative estimation of zirconium: Zeitschr. angew. Chemie, vol. 41, pp. 2110–2111, 1912.
2. Chrustschoff, K., Artificial zircon: Min. Mag., vol. 10, p. 259, 1890.
3. D'Ans, J., and Loffler, J., Untersuchungen in System Na_2O-SiO_2-ZrO_2: Zeitschr. f. anorg. Chemie, vol. 191, pp. 1–36, 1930.

4. Deville, Sainte-Claire, Mode de formation de la topaze et du zircon: Acad. Sci. Paris Comptes rendus, vol. 52, pp. 780–790, 1861.
5. Gruner, J. W., The hydrothermal alteration of feldspars in acid solutions between 300° and 400° C: Econ. Geol., vol. 39, pp. 578–589, 1944.
6. Hautefeuille, P., and Perry A., Sur la reproduction du zircon: Acad. Sci. Paris Comptes rendus, vol. 107, pp. 1000–1001, 1888.
7. Lenher, J., and Merril, H. B., The solubility of silica: Amer. Chem. Soc. Jour., vol. 39, pp. 2630–2639, 1917.
8. Morey, G. W., and Fenner, C. N., The ternary system H_2O-K_2SiO_3-SiO_2: Amer. Chem. Soc. Jour., vol. 39, pp. 1173–1229, 1917.
9. Smith, F. G., Transport and deposition of the non-sulphide vein minerals. I. Introduction: Econ. Geol., vol. 41, pp. 57–63, 1946.
10. ——, Transport and deposition of the non-sulphide vein minerals. II. Cassiterite: Econ. Geol., vol. 42, pp. 251–264, 1947.
11. ——, Transport and deposition of the non-sulphide vein minerals. III. Phase relations at the pegmatitic stage: Econ. Geol., vol. 43, pp. 535–546, 1948.
12. ——, Transport and deposition of the non-sulphide vein minerals. IV. Tourmaline: Econ. Geol., vol. 44, pp. 186–192, 1949.
13. Washburn, E., The system ZrO_2-SiO_2: Amer. Ceramic Soc. Jour., vol. 3, pp. 634–640, 1920.
14. Winchell, A. N., The microscopic characters of artificial inorganic solid substances or artificial minerals, John Wiley and Sons, New York, 1931.

AEROMAGNETIC SURVEY OF THE ALLARD LAKE DISTRICT, QUEBEC.

WESTON BOURRET.

ABSTRACT.

During the summer of 1947 Kennco Explorations, Limited, made an airborne magnetometer survey of a large anorthosite body in eastern Quebec known to contain deposits of ilmenite-hematite. The purpose of the investigation was to determine the regional limits of ilmenite-hematite mineralization and prospect for additional deposits. Over 4,500 linear miles of magnetometer traverse were flown at an elevation of approximately 500 feet above the ground. The general geologic setting and aeromagnetic results are discussed. The survey was not only successful, but was completed in a small fraction of the time that would have been required by ground-traversing methods.

INTRODUCTION.

THE Allard Lake ilmenite-hematite deposits are situated in Saguenay County, Quebec, about twenty-five miles north of Havre Saint Pierre, a small fishing village on the North Shore of the Saint Lawrence Gulf. The area is approximately 400 miles below Quebec City; its position is indicated in Figure 1.

Like most of the North Shore topography, the area presents the appearance of a recently dissected plateau. It contains literally hundreds of small lakes and many streams. While there are no conspicuous peaks or high mountains, in detail the region is very rough and in places precipitous. Steep cliffs several hundred feet high border some of the lakes; the drainage pattern is deeply entrenched with numerous waterfalls and fast rapids. Canoe travel, the principal means of transportation before the fall freeze-up, is arduous, slow and often hazardous.

Where not burnt over, the area is covered with a dense stunted growth of pine, balsam, and spruce.

In 1942 [1] the Quebec Bureau of Mines published the results of a reconnaissance survey of this area made in 1941 by J. A. Retty. Retty describes finding outcrops of ilmenite-hematite on the shores of Lakes Bat Le Diable, Puyjalon, Allard, and Petit Pas. He describes the magnetic nature of the ore, gives as his opinion that the district is well worth prospecting, and that a dip needle survey might be used to advantage in this work. Probably on the basis of Retty's report, several groups of claims were staked in the area, some of which were taken under option by Kennecott Copper Corporation late in 1942.

During the summer of 1944 Dr. W. W. Longley, who had previously worked for the Quebec Bureau of Mines, made an examination of some of these

[1] Retty J. A., Preliminary report on the Lower Romaine River area, Saguenay County, Quebec: Quebec Bur. Mines Prel. Rept. 171, 12 p., 1942.

claims for Kennecott. In 1946 further prospecting was undertaken by Kennco Explorations, Limited, Kennecott's subsidiary, and this work resulted in the discovery of the large orebody now being developed south of Petit Pas Lake.

Early in 1947 preparations were made to fly the area with the airborne magnetometer and during the summer of the same year the survey was made. It was hoped such a survey might serve to outline or delimit the areas of ilmenite-hematite mineralization and in addition simplify the work of "dip needle" ground parties attempting to prospect in the more inaccessible and difficult areas.

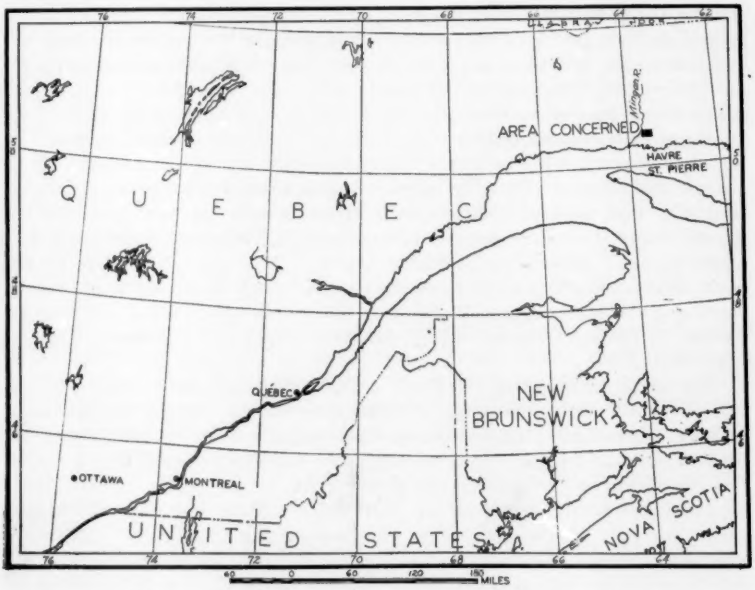


FIG. 1. Index map showing position of area surveyed.

GEOLOGIC SETTING

The entire area is underlain by rocks of Precambrian age, though the south boundary is in close proximity to the contact of the Precambrian with the Paleozoic sediments fringing the Gulf. Bedrock is in places covered by a thin moraine of sand and boulders, but on the whole glacial deposition is not great except over certain broad slopes and in low swampy areas. The muskeg growth is mostly only a few feet in thickness.

From a point near Lac des Eudistes at the western extremity of the area and trending in a northeasterly direction for a distance of some 90 to 100 miles is a large mass of anorthosite and anorthositic gabbro crudely resembling the

shape of a peanut in its broad surface outline. Retty [2] places the various facies of this complex in the Morin Series (Archean) of Eastern Canada; as might be expected, all the titaniferous iron deposits discovered to date occur in this series. The same relationship to anorthositic types apparently also holds for the titaniferous ores in other parts of Quebec Province, as well as the Adirondacks of New York.

The Morin series is contacted along its south and southeastern boundary by Precambrian granite believed younger than the anorthosite and gabbro. The granite is generally of light pink color, coarse textured and porphyritic; in places it is slightly foliated. Tongues and masses of granite are observed intruding the gabbro and anorthosite along the granite-Morin contact. Also pegmatite dikes, probably representing a late phase of the granite, are common along this zone cutting both the granite and the anorthosite-gabbro complex.

The country lying to the northwest of the Morin complex is difficult of access due to its distance from the North Shore; consequently the rocks contacting the anorthositic-gabbro over this portion of the area have been observed only during reconnaissance flights and at the few points on lakes where aircraft could land safely. The country rock is a well banded gneiss, probably Grenville, with generally northeasterly trending foliation. At three widely spaced points the rock examined proved to be a coarse quartz biotite hornblende gneiss. There is no positive evidence proving the age relationship between the anorthositic complex and the gneiss, though the strong foliation and banding of the latter suggests it is older. Retty [3] states that along other points on the North Shore the anorthosite has been found to be younger than the Grenville.

The writer believes that the Morin complex may have been forced into the older Grenville gneisses as a concordant rudely tabular sheet or sill-like mass of large areal extent, but without obvious strongly differentiated stratiform characteristics as are found in a true lopolith. Subsequent glaciation and erosion is responsible for exposing the Morin series.

There are several facies of the anorthosite ranging from the labradorite variety through anorthositic gabbros and ilmenite-rich anorthosite. The most widely distributed variety in the vicinity of Allard Lake is a coarse-grained gray anorthosite, composed essentially of euhedral plagioclase (labradorite?). With the exception of accessory ilmenite-hematite and biotite, ferromagnesian minerals are generally absent. Insufficient field work has been done to suggest, except in a general way, the relationship the gabbro phase bears to the anorthosite. However, it can be stated that the gabbroic facies is most commonly observed near the outer edge or periphery of the Morin complex; it is possible this gabbro facies is slightly later than the anorthosite, or it may mark a roughly comfortable stratiform horizon underlying the anorthosite.

Though anorthositic gabbro has been observed in close proximity to ilmenite ore bodies, in the light of our present knowledge of the area it cannot be said this is a significant or diagnostic factor in the search for ore.

[2] Retty, J. A., Lower Romaine River area, Saguenay County, Quebec: Quebec Dept. Mines Geol. Rept. 19, 31 p., 1944.
[3] Idem.

The gabbro phase contains plagioclase, feldspars, rhombic pyroxene, quartz, apatite, biotite, black iron oxide, and commonly a little pyrite. Actually the rock is more properly a norite.

Ilmenite-rich anorthosites outcrop over fairly large areas in the Allard Lake region; this facies is readily distinguished from normal anorthosite on the aeromagnetic map as is mentioned later in the paper. The rock has a very pronounced granular texture and the weathered product sometimes resembles an iron gossan. It may contain minor amounts of pyrite, pyroxene, apatite, and biotite. Commonly the crystal arrangement and contrasting rock facies is suggestive of the pseudo-stratification observed in norites and ultrabasic rocks elsewhere in the world, *i.e.,* the Bushveld, Sierra Leone and the Stillwater complex, Montana.

A strong and prominent regional pattern of steeply dipping fractures carries through the anorthositic rocks with general strike varying from about 20° west of north to 35° east of north. These fractures have influenced the course of drainage and account for the rugged cliff topography bounding certain lakes. Evidence shows that the fractures have offset some of the ilmenite bodies, so it is obvious faulting is later than the mineralization. The faulting is on a regional scale and could be caused by structural failure of the Morin complex following emplacement and consolidation.

ORE DEPOSITS

Massive deposits of black glistening coarsely granular ilmenite-hematite occur at several locations, but as previously noted, always within the Morin series. The bodies may assume the form of irregular lenses, narrow dikes, large still-like masses, or various combinations of these. All the commercially important deposits are in the vicinity of Allard Lake. The largest known orebody, the Petit Pas, is a gently inclined tabular body, with a vertical thickness of between 100 and 300 feet. Well over one hundred million tons of ore containing from 32 to 35 percent TiO_2 are indicated by core drilling in this one deposit alone.

It is the writer's opinion that the ilmenite-hematite is an original constituent of the anorthosite magma, with the larger deposits of commercial ore representing a late segregation or concentration product during consolidation of the magma. The process probably includes some replacement of the original magmatic minerals. The lower grade disseminated material generally is continuous over a considerable area and commonly exhibits pseudo-stratification to a degree suggesting a differentiated sheet-like habit. The small tabular bodies taking the form of narrow dikes and tongues were probably forced into the country rock somewhat after the segregation of the large massive deposits; this implies emplacement after the anorthosite had consolidated sufficiently to fracture. These small bodies are generally higher in TiO_2 and contain less gangue material than the large deposits.

Polished sections of the massive ore show it is not pure ilmenite, but rather that the ilmenite serves as host mineral for numerous fine parallel lamellae and discs of hematite, together with a little magnetite. This crystallographic inter-

growth resulted from unmixing of an originally homogeneous solid solution. The mixture is so intimate and microscopic that ordinary methods of mechanical separation cannot be employed to produce a merchantable ilmenite concentrate, and smelting must be resorted to. A typical specimen of massive black material contains about 70 percent ilmenite, 20 percent hematite, 3–4 percent magnetite, the balance chiefly pyroxene and feldspar gangue; also there will be observed minor amounts of pyrite, spinel, chalcopyrite and pyrrhotite in some specimens.

Several hundred chemical analyses, made in the laboratories of The New Jersey Zinc Company at Palmerton, Pa., show that the ratio of Fe to TiO_2, remains quite constant. For this reason the specific gravity of the rock provides a fairly reliable indication of the ore grade. High-grade ore will have a density of between 4.50 and 4.60 and contain about 35 percent TiO_2 and 42 percent Fe; the overall average for many of the deposits, however, is somewhat lower.

The ilmenite is magnetic and very sensitive to the ordinary dip-needle; in fact, most specimens respond to an alnico magnet and considerable powdered material can be extracted. X-ray studies made by M. L. Fuller and J. L. Rodda of The New Jersey Zinc Company show the ilmenite definitely contains magnetite and since the presence of this mineral was significant when considering magnetometer work it was of interest to learn approximately what percentage of magnetite was actually present. Scale deflection tests based on synthetic mixtures of pure ilmenite, hematite and magnetite were made and indicate the Allard Lake ore usually has a magnetic content varying from 3.0 percent to as much as 5.0 percent. The average for 21 samples believed representative of several of the larger deposits indicated 3.4 percent magnetite.

AEROMAGNETIC SURVEY

The airborne survey was carried out during June and July of 1947 by Aero Service Corporation of Philadelphia, using magnetometer and recording equipment manufactured and licensed by the Gulf Research and Development Corp. The equipment was installed in a Beechcraft type At 11 twin engine plane. Joseph P. Mullen, pilot for Aero Service did the flying and Frank Morgan was in charge of magnetometer observations. The aircraft was based at the United States Army airfield at Mingan on the North Shore of the Saint Lawrence.

A description of the magnetometer equipment is beyond the scope of this paper. For details the reader is referred to the excellent article by R. D. Wyckoff [4] of the Gulf Research Division. It is appropriate to state here, however, that the airborne instrument is a highly sensitive fluxgate magnetometer that measures the relative total magnetic intensity in a field parallel to the earth's total magnetic vector. The major portion of the earth's field is nullified, leaving only relative differences to be measured and recorded. For a mathematical treatment of the relationship between the total intensity vector

[4] Wyckoff, R. D., The Gulf airborne magnetometer: Geophysics, vol. 13, no. 2, pp. 182–208, April 1948.

and its horizontal and vertical components the reader is referred to the recent article by D. S. Hughes and W. L. Pondrom.[5]

The flight traverses over a major portion of the area were laid out on a one quarter mile interval and flown at a nominal elevation of 500 feet above ground level. Certain areas that showed little promise were traversed at a one-half or one mile interval. Due to the rugged nature of the terrain it was, of course, impossible for the aircraft to maintain the 500-foot elevation; actually, the radio

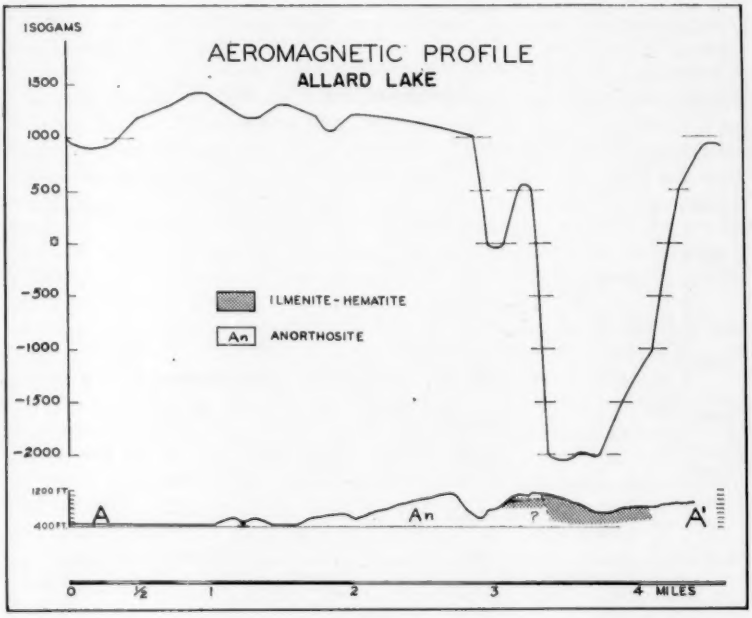


FIG. 2.

altimeter continuous record profile shows the ground distance varied on the average between about 400 and 700 feet; this is a remarkable achievement under such difficult conditions and requires a highly competent pilot and navigator. All lines were flown on a N 45° W bearing, this direction being selected in order that traverses would cross the short dimension of the northeasterly trending anorthosite mass.

The results of each day's flying were transferred to preliminary isogam maps of suitable scale after the profiles were rectified and scale corrected. In practice there was usually a lapse of one or two days between the time actual

[5] Hughes, D. S., and Pondrom, W. L., Computation of vertical magnetic anomalies from total magnetic field measurements: Am. Geophys. Union Trans., vol. 28, no. 2, pp. 193–197, April 1947.

flying was accomplished and translation of the results to the preliminary magnetic relief maps. By keeping the maps up-to-date it was found the work could be better directed and often unnecessary flying avoided, particularly in areas where the contact of the anorthosite with granite or Grenville gneiss was only approximately known. Also the general features of magnetic relief served to show what areas offered promise and should be flown at one-quarter mile interval in contrast to sections of little or no magnetic interest that did not appear

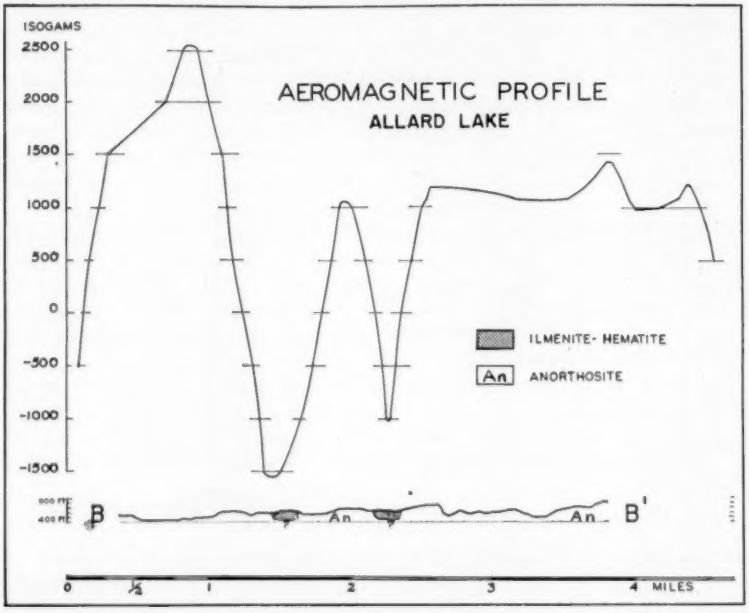


FIG. 3.

to justify detailed study. While the preliminary field map was very generalized, it did serve this purpose. With ilmenite deposits of such strong magnetic characteristics, it was found that variations and discrepancies due to instrument drift and diurnal effect did not introduce sufficient error to change greatly the final map picture. With the completion of the survey, however, these variations have been largely eliminated by adjusting all profile curves to a common magnetic datum established by running a magnetic base line traverse to intersect each flight line.

Some four thousand five hundred linear miles of air traverse were completed and correlated to surface base maps by means of continuous strip photography and interval "fix" points. For construction of the profiles, illustrated in Figure 2 and Figure 3, the isogam interval used was either 100 or 500 gammas,

depending on the amount of detail it was possible for the draftsman to include. The datum, or zero anomaly isogam was selected arbitrarily by inspection.

Discussion of Anomalies.—Within broad limits certain empirical deductions and inferences can be drawn from the survey. The large Petit Pas deposit has been partially outlined by core drilling; the profile shown in Figure 2 illustrates clearly the strong negative anomaly related to this body. The attitude of other bodies is not known. In all instances the large massive deposits gave negative anomalies with very sharp gradients, in the magnitude of 3,000 to 5,000 gammas below the average plateau level. In some instances areas of ilmenite-rich anorthosite also produced negative anomalies, but with less steep gradients. It is of interest to note that in horizontal plan the areal limits of certain anomalies correspond fairly well with the known surface position of the ilmenite bodies. However, since the attitude of the bodies in depth is not known we cannot draw a critical analogy. In the latitude of Havre Saint Pierre the horizontal and vertical components of the earth's field are in the order of 16,000 and 55,000 gammas respectively. Consequently the displacement of anomalies with respect to orebodies occurring close to the surface probably would not be great; as a matter of fact, the map error in location of isogams may amount to as much as 400 or 500 feet, which is probably greater than displacement due to the inclination of the magnetic field.

The strong negative anomalies are believed to result from the effect of negative polarization of the orebody itself. Similar negative observations were obtained when dip needle traverses were run over the same occurrences.

The contact zone between the granite and Morin series produced strong positive anomalies, often in the order of four to five thousand gammas. This is believed due to concentrations of disseminated magnetite in the hybrid rocks of the contact zone. The gabbroic facies of the Morin stands out clearly on the magnetic map in rather marked contrast to normal anorthosite. The anorthosite itself exhibits broad magnetic trends with little relief.

It will be appreciated that the Allard Lake environment proved an ideal setting for employing the airborne magnetometer, not that such a sensitive instrument was required, but simply because the deposits are generally large, the geology relatively simple, and this great area could be prospected easily and rapidly by such a method. While the magnetometer is commonly regarded as an instrument for detailed mapping in most mining investigations, it was possible in this case to employ it as a reconnaissance tool for prospecting on a regional scale.

In future work it appears probable that the principal field for aeromagnetic surveys will be in obtaining the magnetic picture of large areas in connection with regional studies, particularly when a broad relationship exists between rock types and their magnetic properties. The airborne method, combined with photography, offers a rapid and economical means for obtaining a regional geologic picture with a view to screening an area and singling out areas of geological and geophysical interest for more detailed study.

ACKNOWLEDGMENTS.

The writer wishes to express his appreciation and thanks to the various members of Kennco Explorations, Limited and The New Jersey Zinc Company staff who contributed to this investigation, and in particular to Mr. Anton Gray, Chief Geologist of Kennecott Copper Corporation, for critically reading the manuscript and making many helpful suggestions.

KENNECOTT COPPER CORPORATION,
120 BROADWAY,
NEW YORK, NEW YORK,
July 11, 1949.

DISCUSSION AND COMMUNICATIONS

THE EXAMINATION OF SANDS.

Sir: There are certain nonmetallic mineral deposits such as sands and clays which not uncommonly form extensive deposits and may be of considerable commercial importance. The geologist in reporting on these, however, often seems to think that mentioning their type, origin, and possible extent is sufficient. He may not think or realize that they vary greatly in mineralogical character and other properties and from the practical standpoint the amount of information given is quite insufficient.

Sands, which are widely used for different purposes may serve as an example. They vary widely as to mineral composition, texture, shape of the grains, and presence or absence of admixed clay, as well as kind of clay, all of which affect the use of the material. Some can be purified or concentrated, but in many cases this is not practical. Most of the sands and many sandstones are looked upon as being composed mostly of grains of silica, but they may often contain a considerable percentage of feldspar grains, which rules them out for certain uses such as steel foundry work. To judge sands therefore it is necessary to put them through certain tests in order to determine whether they meet the specifications which are set up for foundry, glass, filter, abrasive and other uses.

This means of course that if the geologist is to form any opinion regarding their possible uses, he should have some knowledge of their technology. To do this is not a difficult matter, and considerable information has been published on the subject in concrete form.[1]

To determine these properties requires the collection of samples in the field for laboratory tests, but it would be worth while, and would be of great assistance to persons who are in search of information on the subject.

H. RIES.

CORNELL UNIVERSITY,
ITHACA, N. Y.,
Aug. 29, 1949.

TRANSPORT AND DEPOSITION OF THE NON-SULPHIDE VEIN MINERALS. III PHASE RELATIONS AT THE PEGMATITIC STAGE.

Sir: This is in reply to Dr. G. W. Morey's [1] criticism of the interpretation of experimental results recorded in the above paper.[2]

[1] Am. Inst. Min. Met. Eng., Industrial Minerals and Rocks, 2nd edit., 1949.
[1] ECON. GEOL., vol. 44, pp. 151–154, 1949.
[2] ECON. GEOL., vol. 43, pp. 535, 546, 1948

The schematic diagram given by Dr. Morey (Fig. 1) shows polybaric phase relations for gas—liquid—solid equilibria. This should be compared with the phase relations under isobaric conditions, choosing a pressure higher than the critical pressure of aqueous solutions. (It is legitimate to consider the question in this way, because normal earth temperature—pressure conditions pass far on the high pressure side of the critical point of water.)

At pressures above the critical pressure of aqueous solutions, there is no longer any possibility of gas—liquid equilibria (referring to the aqueous solutions). The properties of water change quite continuously from those of an ideal liquid when it is at a high density, to those of an ideal gas when it is at a low density. Therefore, since there is no discontinuity of properties, there should be no discontinuity of terminology. The term "fluid" is a useful one to designate such a state of matter.

In the paper under discussion, I made it clear that the term "liquid" was being used for fluids with high density. If Dr. Morey chooses to call a dense aqueous solution a gas, it does not alter the phase diagram whatsoever.

The reader is referred to an excellent recent phase study of liquid immiscibility in a silicate—water system by O. F. Tuttle and I. I. Friedman.[3]

F. GORDON SMITH.

DEPARTMENT OF GEOLOGICAL SCIENCES,
UNIVERSITY OF TORONTO,
TORONTO, CANADA,
May 19, 1949.

LIQUID IMMISCIBILITY IN HYDROUS SILICATE SYSTEMS.

Sir: Although I am in complete agreement with the majority of Dr. Morey's recent discussion,[1] I must take issue with his concluding statement, *viz.*—"As far as I can see there is no experimental evidence which makes probable the formation of two immiscible liquids in water-silicate systems."

The evidence for liquid immiscibility in the system H_2O–Na_2O–SiO_2 can be found in a paper by Tuttle and the author published in 1948.[2] Additional experimental work in this system has been done by the author, and will be published shortly. A summary of the experimental evidence for liquid immiscibility follows.

1. Upon quenching runs of the appropriate composition in this system at temperatures above 250° C, one finds that the bomb contains a glass or viscous liquid, plus a liquid whose viscosity is, in general, much less than that of the "heavier" phase.

2. At a constant temperature and Na_2O–SiO_2 ratio the amounts of the two phases can be varied from almost 0 percent to 100 percent by changing the initial total composition.

[3] Amer. Chem. Soc. Jour., vol. 70, pp. 919–926, 1948.

[1] Morey, G. W., Transport and deposition of the non-sulphide vein minerals. III. Phase relations at the pegmatitic stage—a discussion of the above paper: ECON. GEOL., vol. 44, p. 151, 1949.

[2] Tuttle, O. F., and Friedman, I., Liquid immiscibility in the system H_2O–Na_2O–SiO_2: Jour. Am. Chem. Soc., vol. 70, p. 919, 1948.

3. Analyses of the glasses show that their composition is a function of temperature and Na_2O–SiO_2 ratio, and is independent of initial composition, and of degree of filling.

4. The glass or heavy phase is soluble (miscible) in the higher phase at temperatures below approximately 225° C. Therefore, only one liquid phase will be found in runs made below 225° C.

5. As a check, the K_2O–Si_2O–H_2O system [3] originally investigated by Morey was investigated at 350°, 400°, and 450° C.

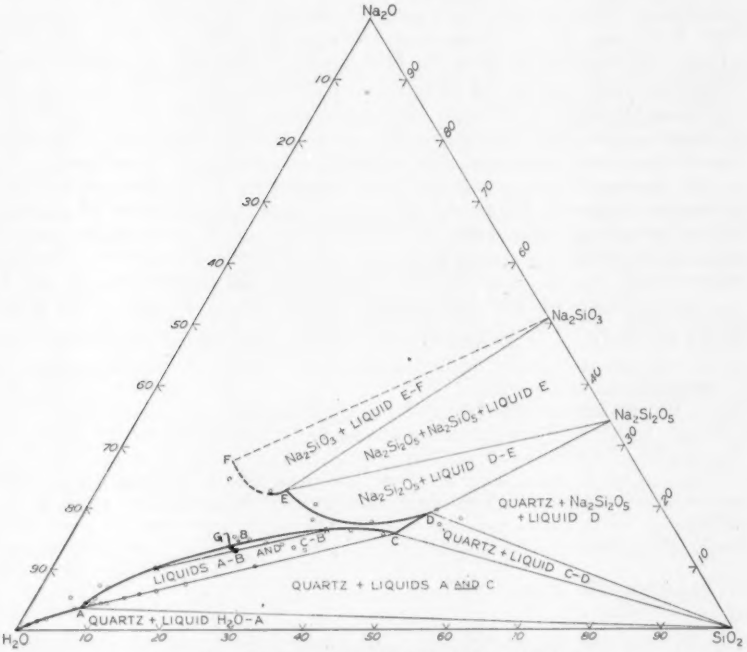


FIG. 1. The system H_2O-Na_2O-SiO_2 at 250° C.

In this system, liquid immiscibility does not occur. For example, in runs made at 350° C, KH Si_2O_5 crystals plus one liquid (practically pure H_2O) was found. As the temperature was raised to 400° C the KH Si_2O_5 "melted" to give a liquid containing approximately 25 percent H_2O, and the solution varporized to give a gas containing less than 1 percent of non-volatile components (K_2O, SiO_2).

Since two liquids are found upon quenching runs made only at temperatures above the critical temperature of the solution, it can safely be assumed

[3] Morey, G. W., The ternary system H_2O–K_2SiO_3–SiO_2: Jour. Am. Chem. Soc., vol. 39, p. 1173, 1917.

that liquid immiscibility does not occur in this system at the temperatures investigated.

This is in contrast to the situation existing in the H_2O–Na_2O–SiO_2 system, where the two liquids do exist at temperatures below the critical temperature of all of the phases.

The possibility that the light liquid is simply the condensed vapor phase is ruled out by the amount of light phase present, as well as the composition of the light phase.

By starting with a composition close to (G) Figure 1, one will get approximately equal amounts of a phase containing (15% SiO_2; 11% Na_2O; 74% H_2O) and a phase whose composition is (37% SiO_2; 16% Na_2O; 47% H_2O). At room temperature the first phase will resemble egg white in viscosity while the second will have the viscosity of honey. The pressure, as estimated by degree of filling, is quite low—below 2,000 psi. On the score of composition alone, it is hard to conceive of a vapor containing such a high concentration of non volatiles at such relatively low temperatures and pressures.

As the temperature is increased, the composition of the light phase tends to become higher in H_2O. At 350°, it contains approximately 95 percent H_2O. According to the work of N. I. Chitarow and L. A. Iwanow [4] such a solution would have a critical end point between 380° and 395° C. Therefore, at temperatures above 400° C the system would contain a liquid plus a gas, and the term "liquid immiscibility" would no longer apply. The comments of Dr. Morey relative to the work of Goranson would then apply.

I. FRIEDMAN.

DEPARTMENT OF GEOLOGY,
UNIVERSITY OF CHICAGO,
CHICAGO, ILL.,
August 16, 1949.

[4] Chitarow, N. I., and Iwanow, L. A., Kritische Temperatur des Wassers und der wässerigen Lösung des kieselsauren Natruims: Zentralblatt für Mineralogie, vol. 1936A, p. 46, 1936.

REVIEWS

Bergwerk- und Probierbüchlein (On Mining Geology and Assaying). A TRANSLATION FROM GERMAN OF TWO 16TH CENTURY WORKS, BY A. G. SISCO AND CYRIL STANLEY SMITH. Pp. 196. Am. Inst. Min. Met. Eng., Seeley W. Mudd Series, New York, 1949. Price, $6.00.

This delightful luxury publication reminds one a little of the Hoover translation of "De Re Metallica" by Georgius Agricola. The two volumes antedated "De Re Metallica" and it is evident that Agricola made much use of the material in these volumes; one recognizes also considerable similarity in the character of the woodcuts that are reproduced. These two books are recognized as constituting the first printed works dealing with the technology of mining and metallurgy.

The *Bergbüchlein,* "The Little Book on Ores," is stated to be the first printed work in the field of mining and is an introduction to mining geology. It describes the ores of the seven most important metals and deals with the theories of ore generation, tools and knowledge needed for mining, and hints on where to find ores. Veins, faults and intersections are described and pictured. Agricola drew heavily on this part. The several woodcuts, carefully reproduced, add charm.

The *Probierbüchlein,* "The Little Book on Assaying," is the first printed work on metallurgy and appeared, first, about 1520. It gives information on the art of assaying, cupelling, dissolving metals and of polishing gems. It also has many woodcut illustrations.

The translators have made charming reading the historical and cultural aspect of which will be appreciated by all members of the mining fraternity. As Mr. A. B. Parsons states in the Preface "they contain descriptions and dissertations that make fascinating reading 400 years after they were written."

This small volume will be treasured by all who read it as "a delightful translation of the first treatises on the technology of minerals and metals ever recorded on the printed page." Congratulations to the Institute and to the Seeley W. Mudd Memorial Fund Committee!

ALAN M. BATEMAN.

Sedimentary Rocks. By F. J. PETTIJOHN. Pp. 526; pls. 40; figs. 131. Harper & Brothers, New York, 1949. Price, $7.50.

In this book the author states that he is dealing with sedimentary rocks rather than sedimentation, with the products of weathering, transportation, deposition, diagenesis and lithification, rather than the processes, and with the properties of sediments rather than the mechanics of sediment analysis. He also has incorporated much significant data acquired by quantitative methods of analysis during the past twenty years, and he has described and interpreted sedimentary rocks in the light of this new information. In so doing he points out certain gaps in our knowledge.

Broadly speaking the author has aimed to make this volume a guide to the observation, classification, and interpretation of sediments and sedimentary rocks in the field and in the laboratory. These aims have been admirably accomplished, and

as a consequence the author has produced an excellent textbook for teachers and students and a valuable reference book for professional geologists and others.

The style of the writer is direct, lucid, and stimulating, the point of view is faithfully scientific yet clearly directed by a sense of conviction from his breadth of knowledge and experience, and the organization is patent to the aims of the book.

The illustrations are excellent with photographs and photomicrographs in collotype. Tables of quantitative data and graphs appear throughout. The references are numerous and well selected, and placed at the bottom of the page where they ought to be. The format and typography seem also to finish off this work and will contribute to the happy reception which this book is destined to receive.

MORRIS M. LEIGHTON.

URBANA, ILL.,
Sept. 6, 1949.

Mines Register, Successor to the Mines Handbook, Vol. 23. 1949 Edit. Pp. 730. Atlas Publishing Co., 425 West 25th St., New York, 1949. Price, $25.00.

This widely consulted series in its 1949 volume is larger and has more coverage than the 1946 edition. It contains information on 5,000 active non-ferrous mines in the Western Hemisphere, giving location, history, officers and mining personnel, capitalization, earnings, dividends, ore reserves, property, equipment and recent production. It also lists 22,000 inactive mines and their location. Special sections deal with metal industry statistics, mine officials and operators, securities and price ranges from 1940 to 1948. There is also the customary buyers guide and equipment manufacturers.

The volume is indispensable to engineers, mining companies, financial people, investors, bureaus, and publishers.

Hydrology. By C. O. WISLER AND E. F. BRATER. Pp. 419; figs. 132; tbls. 29. John Wiley & Sons, Inc., New York, 1949. Price, $6.00.

This compact book on an increasingly important subject presents fundamental principles of hydrology and emphasizes the practical problems relating to stream flow records, average yield, minimum flow, flood flow, and flood control. It deals with these problems more from the standpoint of the practicing engineer and the forester, than from that of the student.

Its highly practical character is based upon a scientific approach and these combined should make it a very usable volume.

Subsurface Geologic Methods—A Symposium. COMPILED AND EDITED BY L. W. LEROY AND HARRY M. CRAIN. Pp. 826; figs. 437; tbls. 33; pls. 12. Colorado School of Mines Quarterly, Vol. 44, No. 3, July 1949. Price, $6.00.

There is brought together in this volume, for the first time, discussion of the various subsurface procedures that are used. There are 41 contributors who cover 43 major topics, divided into the following 12 chapters: Stratigraphic, Structural, and Correlation Considerations; Subsurface Laboratory Methods; Subsurface Logging Methods; Miscellaneous Subsurface Methods; Subsurface Graphic Representations; Subsurface Maps and Illustrations; Reports on Subsurface Geology; Subsurface Methods as Applied in Geophysics; Subsurface Methods as Applied in Mining Geology; Geologic Techniques in Civil Engineering; Sources of Subsurface Information. It covers the various types of logging methods, core examination, micropaleontology, mineralogic and sedimentation methods, microscopic, thermal

analyses and X-ray methods. The volume also deals with the various methods of representing the results on maps, sections and charts.

It is a very thorough coverage and the Colorado School of Mines deserves much credit for producing it.

BOOKS RECEIVED.

CHARLES H. SMITH.

U. S. Bureau of Mines—Washington, D. C., July–August 1949.

Rept. Inv. 4420. Chemical Analysis of Clay. HASKIEL R. SHELL. Pp. 36; fig. 1; tbl. 1. *Presents methods of chemical analysis of clays for moisture, ignition loss, SiO_2, Al_2O_3, Fe_2O_3, TiO_2, P_2O_5, CaO, MgO, Na_2O, K_2O, total carbon, carbonate carbon, total sulfur, soluble salts and soluble sulfate.*

Rept. Inv. 4490. Zinc-Lead Ore Reserves of the Tri-State District, Missouri-Kansas-Oklahoma. OTTO RUHL, SIMEON A. ALLEN AND STEPHEN P. HOLT. Pp. 59; figs. 8; tbls. 9. *Ore reserves are estimated at 66,100,000 tons of minable ore containing 2.16% Zn and 0.38% Pb.*

Rept. Inv. 4503. Investigation of Salt River Range Vanadium Deposits, Lincoln County, Wyo. PAUL T. ALLSMAN, FOREST H. MAJORS, STANFORD MAHONEY AND W. A. YOUNG. Pp. 18; figs. 6. *Tightly folded vanadiferous-shale beds assaying 0.866 V_2O_5, outcrop for over 18 miles.*

Rept. Inv. 4506. Investigation of Montezuma and Chinati Zinc-Lead Deposits, Shafter District, Presidio County, Tex. W. D. MCMILLAN. Pp. 26; tbls. 2; figs. 8. *Results of investigations to develop replacement ore bodies in limestone beds adjacent to mineralized faults. Ore minerals are largely oxidized and consist of anglesite, cerussite, smithsonite and limonite in a gangue of altered limestone, calcite and quartz.*

International Coal Trade. Fuels and Explosives Division, Vol. 18, No. 7. Pp. 51; tbls. 67. *67 tables related to coal trade in North America and Europe; production, imports and exports, consumption, etc.*

Mineral Resources and Mineral Production During 1947. UNDER DIRECTION OF OLAF P. JENKINS. Pp. 197; fig. 1; pls. 12; tbls. 54. California Division of Mines Bull. 12, San Francisco, 1949. *Geology, mineral resources, mining activity and production of each county described.*

Illinois State Geological Survey—Urbana, 1949.

Circ. 151. Coal Resources of Franklin County, Illinois. GILBERT H. CADY. Pp. 12; figs. 5; tbls. 4. *Brief notes on geology and data on depletion, tonnages and future of the coal beds.* **Oil Accumulation in the Cypress Sandstone in the Herald Pool, White and Gallatin Counties, Illinois.** NANCY MCDURMITT. Pp. 8; figs. 5; tbl. 1. *Description of structural and stratigraphic traps in the Cypress sandstone.*

Circ. 153. Flooding with Re-used Water. FREDERICK SQUIRES. Pp. 3; figs. 2. *Describes a method of injecting water from an upper flooded-out oil sand to flood a lower oil sand.*

Developments in Illinois and Indiana in 1948. ALFRED H. BELL, R. E. ESAREY AND B. E. BROOKS. Pp. 11; figs. 2; tbls. 9. Press Bull. Series 59, *Oil and gas.*

Directory of Geology Departments of Educational Institutions in the United States and Canada. Compiled by Dorothy Johnson, Shepard W. Lowman and John T. Rouse. Pp. 136. Amer. Ass. Petroleum Geologists, Tulsa, Okla., March 1949. Price, $1.50. *Lists staff, courses and degree requirements.*

Kansas Geological Survey—Lawrence, 1949.

Bull. 79. Geology and Ground-Water Resources of a Part of South-Central Kansas, With Special Reference to the Wichita Municipal Water Supply. Charles C. Williams and Stanley W. Lohman. Pp. 455; pls. 34; figs. 31; tbls. 37. *Describes geography, geology and ground water resources of Mac Pherson County and parts of Harvey, Sedgwick, Reno and Marion Counties. Includes detailed description of the geologic formations and their water-bearing properties.*

Bull. 82, Pt. 2. Preliminary Report on Phosphate-Bearing Shales in Eastern Kansas. Russell T. Runnels. Pp. 11; pls. 2; tbls. 6. *Chemical analyses of Pennsylvanian phosphate-bearing bituminous shales from Crawford, Bourbon, Franklin, Labette and Wyandotte Counties.*

Insoluble Residues of Some Paleozoic Formations of Missouri, Their Preparation, Characteristics and Application. John G. Grohskopf and Earl McCracken. Pp. 39; pls. 11. Missouri Geol. Survey Rept. Inv. 10, Rolla, 1949.

New York State Department of Conservation—Albany, 1945 and 1948.

Bull. GW–12. The Water Table in the Western and Central Parts of Long Island, New York. C. E. Jacob. Pp. 24; pls. 2.

Bull. GW–13. The Configuration of the Rock Floor in Western Long Island, N. Y. Wallace deLaguna and M. L. Brashears, Jr. Pp. 32; tbl. 1; map 1.

Bull. GW–17. Geologic Correlation of Logs of Wells in Kings County, New York. Wallace deLaguna. Pp. 35; tbls. 2; pls. 3.

Rhode Island Industrial Commission—Providence, 1945 and 1948.

Geol. Bull. 1. Progress Report on the Ground Water Resources of Providence, Rhode Island. Claude M. Roberts and M. L. Brashears, Jr. Pp. 35; figs. 2; maps 2; tbls. 3.

Geol. Bull. 2. Well and Test Hole Records for Providence, Rhode Island. Claude M. Roberts and Henry N. Halberg. Pp. 52; maps 2.

Geol. Bull. 3. The Geology and Ground-Water Resources of the Pawtucket Quadrangle, Rhode Island. Alonzo Quinn, R. G. Ray, W. L. Seymour, N. E. Chute and W. B. Allen. Pp. 85; pl. 1; figs. 7; tbls. 9; maps 3. *Describes geologic formations, surface geology and ground-water resources.*

Pre-Chattanooga Stratigraphy in Central Tennessee. Charles W. Wilson, Jr. Pp. 407; figs. 89; pls. 28. Tennessee Div. Geology Bull. 56, Nashville, 1949. *Detailed account of Ordovician, Silurian and Devonian stratigraphy; also structure and geologic history.*

Ontario Department of Mines—Toronto, 1949.

Bull. 25. List of Publications, Including Reports (Vols. I–LVIII, 1891 to 1949), Maps, and Bulletins. Pp. 56; maps 2.

General Index to the Reports, Vols. XXXVI to XLIX (1927–1940). Compiled by E. A. Trevor. Pp. 505.

Notes on Tin and Wolfram in Burma and India. E. L. G. Clegg. Pp. 168; tbls. 14; pls. 6. India Geol. Survey Records, Vol. LXXVI, Bull. of Econ. Minerals 15, Calcutta, 1944 (1948). Price, 13 sh. *Much valuable information on the tin and wolfram industries as well as the geology of their occurrences.*

Federation of Malaya Geological Survey—Batu Gajah, 1949.

A Short Account of the Deep Alluvial Tin Deposits of Malaya near the Granite-Limestone Contact. F. T. Ingham. Pp. 9; figs. 3; pl. 1. *Discusses mode of formation of alluvial tin deposits along a granite-limestone contact, and describes some of them.*

Report of the Geological Survey Department for the Year 1948. F. T. Ingham. Pp. 59; maps 3.

Les Rapports Numériques et Volumiques de l'Oxygène dans les Minéraux et les Roches. Boris Brajnikov. Pp. 28; tbls. 5; figs. 2. Minas Gerais Instituto de Tecnologia Industrial, Belo Horizonte, 1949. *Numerical and volumetric relations of oxygen in minerals and rocks.*

Um Perfil Geológico de Região de Coimbra. G. Soares de Carvalho. Pp. 10; figs. 7; tbl. 1. Coimbra, Portugal, 1949. *Coimbra geological formations consist of (1) continental formations: a) with 2 systems, mostly eolitic deposits, b) lacustrian deposits between the 2 systems; (2) marine formations, and probably lagunar in part, over the continental formations.*

Les Dépôts des Terrasses et la Paléo-géographie du Pliocène dans la Bordure Mesocenozoïque Occidental du Portugal, entre le Vouga et le Mondego. G. Soares de Carvalho. Pp. 24; figs. 17; tbls. 3. Coimbra, Portugal, 1949. *Distinguishes three types of deposits—fanglomerate, marine and fluvial, corresponding to an upper Miocene regression, a middle Pliocene transgression and the Villafranchian regression.*

Estudos, Notas e Trabalhos, Vol. 4, Fasc. 2. Pp 109; numerous photographs and maps. Servico de Fomento Mineiro, Porto, Portugal, 1948. *Two papers; on deposits of calamine and smithsonite in southern Portugal and a chronological historical account of petroleum examinations in Portugal. Also a résumé of activities of the Mines Branch during the first half of 1948.*

Les Ressources Minérales du Congo Belge et du Ruanda-Urundi. A. Jamotte and J. Lepersonne. Pp. 17; tbl. 1; pls. 4. *Brief description of geology and mineral resources—gold, tin, copper, diamond, cobalt, zinc, cadmium, uranium, silver, platinum, palladium, lead, nickel, molybdenum, vanadium, tungsten, columbo-tantalite, iron, nonmetallics.*

Présentation d'une Carte Géologique du Congo Belge à l'Echelle du 1.000.000e. L. Cahen and J. Lepersonne. Pp. 4. *Presentation of Belgian Congo geological map on the scale of 1/1,000,000.*

Diamanten. Felix Hermann. Pp. 135; pl. 1. Donau-Verlag, Vienna, 1948. *A history of the diamond through the centuries.*

Words into Type. Marjorie E. Skillin, Robert M. Gay et al. Pp. 585. Appleton-Century-Crofts, Inc., New York, 1949. Price, $5.00. *Most useful book for authors, editors, proof readers. Deals with manuscripts, techniques for copy and proof, typography and illustrations, printing style, grammar, and use of words; 4 appendices.*

SCIENTIFIC NOTES AND NEWS

J. M. HANSELL has been transferred from Dallas, Texas, to Calgary, Alberta, where he has become Chief Geologist for the Canadian Division of the Sun Oil Co.

The offices of the Ground Water and Surface Water Branches, U. S. Geological Survey, have been changed from 222 Old Country Road to 230 Old Country Road, Mineola, Long Island, N. Y.

LEONARD W. ORYNSKI announces the opening of his office as Consulting Geologist, oil royalties, at 604 Republic Bank Bldg., Dallas, Texas.

The annual Fall Regional Meeting of the Industrial Minerals Division, AIME, was held in Tampa, Florida, November 8–12, 1949. Technical papers on geology, mining and milling of Florida phosphates and other mineral resources, and papers on industrial minerals in the southeastern states were presented. The meeting was highlighted by several field trips.

CHINGYUAN Y. LI, Regional Vice-President for Asia of the Society of Economic Geologists, has gone to Bangkok, Siam, to serve, on a loan base from the Chinese Government, as a U. N. Consultant on coal and iron ores to make a regional study of these basic mineral resources in Asia and the Far East.

JESSE C. JOHNSON has been appointed to the newly-established position of Deputy Manager, AEC Raw Materials Operations Office, Washington, D. C. Mr. Johnson has been serving as Assistant Manager of the Raw Materials Operations Office, in charge of domestic production, since January, 1948. As Deputy Manager, Mr. Johnson will assist Manager John K. Gustafson in administering the entire AEC program for the acquisition and production of all raw materials, including uranium, used in the national atomic energy program.

EMMONS MEMORIAL FELLOWSHIP

The S. F. Emmons Memorial Fellowship in Economic Geology is available for the academic year 1950–1951, with a stipend of $1,200.00. Applications and accompanying testimonials should be submitted not later than March 1, 1950. Applicants should be qualified by training and experience to investigate some problems in Economic Geology and should submit a definite statement of the problem to the Committee, under whose oversight the work may be undertaken at any institution approved by them. The Fellow must give entire time to the problem, which may be used for a doctorate dissertation. Application blanks may be obtained from Alan M. Bateman, Yale University, L. C. Graton, Harvard University, Paul F. Kerr, Columbia University, or the Secretary, Columbia University.

INDEX TO VOLUME XLIV

[NOTE.—In this index the title of principal papers and headings of departments, as *Discussions* are in italics.]

Abstracts—

Aeromagnetic survey of the Allard Lake district, Quebec (Bourret), 732

Buried preglacial ground water channels in the Albany-Schenectady area in New York (Simpson), 713

Canada's resources of low-rank coals (MacKay), 644

Cannel, boghead, torbanite, oil shale (Schopf), 68

Coal geology: An opportunity for research and study (Cady), 1

Coals of Texas (Stenzel), 638

Deposition and resolution of native silver at Gowganda, Ontario (Bastin), 437

Determination of reflectivity of the ore minerals (Folinsbee), 425

Device for calculating stoping values from assays of narrow veins (Kruger), 445

Differentiation of titaniferous magmas (Evrard), 210

Discovery of nickel in Egypt (Nassim), 143

Distribution, classification and utilization of western U. S. coals (Parry), 643

Distribution, occurrence, and resources of sub-bituminous coal and lignite in the western United States (Bryson), 643

Electron microscopy of coal (McCartney), 617

Favorable ore zones of the Northport district, northeastern Washington (Campbell), 639

Field method for the determination of zinc in soils (Lakin, Stevens, and Almond), 296

Field relations of Arkansas bauxite deposits (Gordon, Tracey, and Ellis), 640

Geochemical prospecting for ores: A progress report (Hawkes), 80, 706

Geological and botanical study of the Brandon lignite and its significance in coal petrology (Barghoorn), 645

Geological explanation of geophysical anomalies near Cerro de Pasco, Peru (Kruger and Lacy), 485

Geological features of North Dakota lignites (Roe), 644

Geology and ground water of the Azapa valley, Province of Tarapacá, Chile (Taylor), 40

Abstracts—Continued

Geology of the Cerro Gordo mine area, Inyo County California (Merriam), 82

Geology of the Helvetia mining district, Pima County, Arizona (Johnson), 639

Geology of the massive sulphide deposits at Iron Mountain, Shasta County, California (Kinkel and Albers), 81

Ground-water resources of the El Paso region (Sayre), 638

Logarithmic pattern in river deposits (Wertz), 193

Metallurgical limestone reserves (Landes), 641

Method for polishing sections of ores (Sampson), 119

Mining geology and the engineering aspects of mineral exploration (Forrester), 545

Monzonite intrusion and mineralization in the Coeur d'Alene district, Idaho (Anderson), 169

National mineral resource appraisal (Lasky), 82

Notes on iron ores of central Minas Gerais, Brazil (Dorr and Guild), 646

Ore deposits of the Wallapai district, Arizona (Thomas), 663

Origin of the Bendigo saddle reefs with comments on the formation of ribbon quartz (Chace), 83, 561

Origin of the epithermal mineral deposit (Schmitt), 641

Origin of the mercury minerals of the Terlingua district, Brewster and Presidio Counties, Texas (Yates and Thompson), 640

Oxidation and enrichment in the San Manuel copper deposit, Arizona (Schwartz), 81, 253

Paikungshan coal field—A new discovery in the Huainan Basin, northern Anhui, central China (Hsieh), 128

Papers to be presented at the Twenty-ninth Annual Meeting, 79

Papers to be presented at the Thirtieth Annual Meeting, 638

Paragenesis of accessory minerals in igneous rocks (Moorhouse, Peach, and Buchanan), 642

Patterns of ore deposition in Mexico (Behre, *et al.*), 638

Pegmatites of Montana (Heinrich), 307

Petrographic analysis of coal by the particle count method (Parks), 376

Abstracts—Continued
Petrography of American lignites (Parks), 645
Precipitation of basic copper (Garrels, Howland, and Dreyer), 641
Problems of coal geochemistry (Miller), 649
Relationship of contact-metamorphic-tungsten deposits to regional geology in the Bishop district, California (Bateman), 79
Research in coal paleobotany since 1943 (Schopf), 492
Results from preliminary studies of vein formation at Butte, Montana (Sales and Meyer), 465
Ribbon structure in gold-quartz veins (McKinstry and Ohle), 87
Scheme of the chemistry of the ore veins based on qualitative spectrographic analysis (Kutina), 642
Sedimentation: An appropriate field of research in the natural history of coal beds (Dapples), 598
Sheet structure, a major factor in the occurrence of ground water in the granites of Georgia (LeGrand), 110
Some glass sands from New Jersey (Wilkerson and Comeforo), 63
Some occurrences of chromite in New Caledonia (Maxwell), 525
Status of work on coal resources in the United States (Averitt), 646
Structural control and mineralization at the Seventy Nine mine, Gila County, Arizona (Kiersch), 24
Structures due to volume shrinkage in the bedding-replacement fluorspar deposits of southern Illinois (Grogan), 606
Suggested origin for the Shelby County, Alabama, limonite ores (Allen), 278
Thermal springs and their possible significance in the future discovery of ore deposits (White, Thompson, and Brannock), 83
Transport and deposition of the non-sulphide vein minerals. IV. Tourmaline (Smith), 186
Transport and deposition of the non-sulphide vein minerals. V. Zirconium minerals (Maurice), 721
Uniformitarianism and the ideal vein (Schmitt), 80
Utilization of induced stream infiltration and natural aquifer storage at Canton, Ohio (Kazmann), 84, 514
Variations in garnierite from the nickel deposit near Riddle, Oregon (Pecora, Hobbs, and Murata), 13
Vein features in the Ouachita mineral province, Arkansas (Engel), 79

Abstracts—Continued
Vestigial zinc in surface residuum associated with primary zinc ore in east Tennessee (Hawkes and Lakin), 286
Wall rock replacement by oxidized copper minerals (Dreyer, Howland, and Garrels), 642
Actinolite, 331
Adams, G. I., on brown ores, 283
Adams, S. F., on quartz, 93, 577
Aegirine, 331, 333
Aerial photos and preparation of geologic maps (communication), 551
Aeromagnetic survey of the Allard Lake district, Quebec, (Bourret), 732
Ahlfeld, F., on tin ores, 240
Alabama, limonite ores, A suggested origin for the Shelby County (Allen), 278
Cretaceous, 621
Albany-Schenectady area in New York, Buried preglacial ground water channels in the (Simpson), 713
Albers, J. P., with Kinkel, A. R., Jr., abstract by 81
Alberta, lignite (abstract), 644
Albite, 175, 188, 191
Alcock, F. J., Appalachian region, Canada (review), 72
Alexander, L. T., Byers, H. G., and Edgington, G., on Dewey silt loam, Ala., 291
Alexeeva, E. F., and Godlevsky, M. M., on hydrosilicates, 22
Algae, boghead, 69
Allanite, 176, 314, 324
Allard Lake district, Quebec, Aeromagnetic survey of the (Bourret), 732
Allen, R. M., *A suggested origin for the Shelby County, Alabama, limonite ores,* 278–285
Allen, V. T., on clay, 453
Alluvium, geochemical prospecting, 708
Almond, H., with Lakin, H. W., and Stevens, R. E., *Field method for the determination of zinc in soils,* 296–306
Alteration, bleached zones, Coeur d'Alene, Idaho, 180
Butte district, Mont., 474
Cerro de Pasco, Peru, 485
San Manuel area, Ariz., 265
Seventy Nine mine, Ariz., 37
slate, 591
Wallapai district, Ariz., 684, 698
Altshuler, H. I., on ore, 445
Alumina, vegetal ash content over clays, 451
Alunite, 488
Alunitization, Cerro de Pasco, Peru, 485
Amblygonite, decrepitation, Manitoba, 450
America, petroleum (review), 629
Americas, maps (review), 458
Amethyst, 320, 323
Amin, M. S., on chromite, 538

Analysis of coal by the particle count method, Petrographic (Parks), 376
Anderson, A. L., *Monzonite intrusion and mineralization in the Coeur d'Alene district, Idaho*, 169–185
on quartz monzonite, 180
on sericite rock, 181
Anglesite, 39, 682
Ankerite, 101, 571, 574, 578, 585, 592
Anomalies near Cerro de Pasco, Peru, Geological explanation of geophysical (Kruger and Lacy), 485
Anthraxylon, 4
Antiquity, Ab Swayel copper mine, Egypt, 143
Apatite, 176
Argentite, 438, 683
Arizona, Ore deposits of the Wallapai district (Thomas), 663
Oxidation and enrichment in the San Manuel copper deposit (Schwartz), 253; abstract, 81
Structural control and mineralization at the Seventy Nine mine, Gila County, (Kiersch), 24
Helvetia district (abstract), 639
Arkansas, bauxite (abstract), 640
veins, Ouachita mineral province (abstract), 79
Arsenides, 439, 442
Arsenopyrite, 90, 584, 676, 681
Artesian wells, granite terranes, Ga., 118
Aquifier storage at Canton, Ohio, The utilization of induced stream infiltration and natural (Kazmann), 514
Asbestos, chrysotile, genesis, Australia, 340
Libby, Mont., 333
Ashley, G. H., *The new coal age*, 161–168
on coal, 166
Assaying (review), 745
Assays of narrow veins, A device for calculating stoping values from (Kruger), 445
Atacamite, deposition (abstract), 641
Austin, W. L., on Riddle district, Ore., 14
Australia, chrysotile, genesis, 340
spores in coal, 504
tantalum, 236; (discussion), 336
Averitt, P., abstract by, 646
Axelrod, J. M., on quartz, 297
x-ray analyses by, 20
Azapa valley, Province of Tarapacá, Chile, Geology and ground water of the (Taylor), 40

Backlund, H. G., on granitization, 341
Bacteria and coalification, 657
Baddeleyite, 315, 721, 728
Bain, G. W., on replacement deposits, 36
Baker, J. S., on tantalum, 336
Ball, C. G., on coal, 389
Ball, S. H., on titaniferous ore, 228
on turquoise, 700
Balsley, J. R., Jr., on magnetite-ilmenite deposits, 211
Bannister, C. O., and Garland, H., analysis by, 144
Barghoorn, E. S., abstract by, 645
Barghoorn, E. S., and Linder, D. H., on fungi, 508
Barrell, J., on pegmatites, 308
Barton, H. E., oil, Steamboat Butte field, Wyo. (review), 155
Bastin, E. S., *Deposition and resolution of native silver at Gowganda, Ontario*, 437–444
discussion of papers by, 233
on fluorite, 606
on Gowganda area, Ont., 437
on graphite, 326, 330
on silver, 664
Bastin, E. S., *et al.*, on paragenesis, 673
on replacement, 581
Bateman, A. M., on breccias, 96
on ferric sulphate, 681
on metallogenetic provinces, 337
on ore deposits, 624
on replacement, 582
on ribbon structure, 88
reviews by, 72, 745
Bateman, A. M., and Lasky, S. G., on covellite, 272, 474
Bateman, P. C., abstract by, 79
Batholiths and ore, 341
Bauerman, H., and LeNeve, F. C., on slag, 149
Bauxite, Arkansas (abstract), 640
Bayley, W. S., on ilmenite, 228
Beach, J. H., petroleum, Edison field, Calif. (review), 155
Beck, R., an plants, 709
Becker, G. F., and Day, A. L., on crystals, 590
on ribbon structure, 92
Behre, C. H., Jr., *et al.*, abstract by, 638
Belgian Congo, placers, logarithmic concentration, 207
Bendigo saddle reefs with comments on the formation of ribbon quartz, Origin of the (Chace), 561
Bennett, J. G., on coal, 406
Berkey, C. P., on buried channels, 714
Berl, E., and Keller, H., on coal, 654
Berl, E., and Schmidt, A., on coal, 654
Berry, G. F., Jr., and Harper, P. A., oil, Augusta field, Kan. (review), 155
Beryl, 321
Beyschlag, F., Vogt, J. H. L., and Krusch, P., on pneumatolysis, 624
Bibliography, chromite, New Caledonia, 543
coal, geochemistry, 660
geology, 11
copper-nickel deposits, Egypt, 150
fluorite, shrinkage structures, Ill., 616
garnierite, Oregon, 23
geochemical prospecting, 710

Bibliography—Continued
mining geology, 550
ore and granitization, 346
ore deposits, Wallapai district, Ariz., 703
pegmatites, Montana, 334
reflectivity of ore minerals, 436
sedimentation, coal beds, 605
spores, 512
titaniferous ores, 227, 230
tourmaline synthesis, 192
zinc determinations of soils, 306
zirconium minerals, 730
Biggs, B. S., on degradation products, 658
Billings, M. P., on veins, 672
Biltz, W., and Mecklenburg, Z., on zirconium, 722
Biotite, 175, 199, 331, 333
Bismuth, 441
Blackburn, K. B. and Temperley, B. N., boghead alga, 69
Blanchard, R., on cassiterite-sulphide ores, 239
on chromite, 527
on lead, 708
on scorodite, 681
Blanchard, R., and Boswell, P. F., on copper, 708
Bleached zones, Coeur d'Alene, Idaho, 180
Boggs, H. M., and Alben, A. O., on zinc, 297
Boghead, torbanite, oil shale, Cannel (Schopf), 68
Bogs, geochemical prospecting, 708
Bolivia, tin ores (discussion), 240
Bonetti, E., review of book by, 629
Book structure, 88, 561
Books received, 74, 156, 244, 353, 459, 556, 630, 747
Borings, San Manuel district, Ariz., 258
Bornite, 266, 272, 469, 481, 698
Boswell, P. F., and Blanchard, R., on gangue, 681
Bourret, W., *Aeromagnetic survey of the Allard Lake district, Quebec*, 732–740
Boxwork, garnierite-quartz, 16
Brammall, A., on diabase, 338
Brannock, W. W., with White, D. E., and Thompson, G. A., abstract by, 83
Brazil, iron, Minas Gerais (abstract), 646
Breccias, 590
domino breccia, 105
quartz, 576, 578
silver ores, 441
Wallapai district, Ariz., 696
Bridge, J., on Mascott-Jefferson City area, Tenn., 287
Brinkmann, R., review of book by, 555
Brochantite, deposition (abstract), 641
Brock, R. W., on mineral exploration, 545
Broderick, A. T., books received, 74, 156, 244, 353, 459
Broderick, T. M., *Exploration for ore deposits*, 357–375
Brooks, A. H., on placers, 206
Brown, J. S., review of book by, 554
Brown coal, Texas (review), 638
Brownlee, K. A., on variance, 304
Bruce, E. L., on porphyry, 340
Brüggen, J., on Cretaceous, Tarapacá Province, Chile, 46
Brunton, G., and Caton-Thompson, G., on copper, 143
Bryson, R. P., abstract by, 643
Buddington, A. F., on Adirondack Mtns., N. Y., 210
Buerger, N. W., on sulphides, 476
Burchard, E. F., on brown ores, 283
Burgess, C. H., on pegmatites, 332
Butler, B. S., on alteration, 686
Butler, B. S., and Wilson, E. D., on ore deposition, 696
Butte, Montana, Results from preliminary studies of vein formation at (Sales and Meyer), 465
Butts, C., on Shelby mining district, Ala., 279

Cadman, W. H., on torbanite, 68
Cadmium, interference with zinc tests, 302
Cady, G. H., *Coal geology: An opportunity for research and study*, 1–12
on coal, 379, 398
on geochemistry, 650
on phyteral, 5, 494
Cady, R. C., on ground water, 117
Caillère, S., on hydrosilicates, 22
Calcite, 331, 333, 438, 441, 678
California, Cerro Gordo area (abstract), 82
ground water, Los Angeles Co. (by title), 84
Mother Lode region (review), 74
sulphides, Iron Mtn. deposits (abstract), 81
tungsten, Bishop district (abstract), 79
vein structures, Mother Lode, 91
Campbell, A., on silver ore, 437
Campbell, C. D., abstract by, 639
Campbell, M. R., on coal, 164
Canada, coal, reserves, 165
lignite (abstract), 644
map (review), 458
Mines Register (review), 746
ore deposits, structure (review), 72
petroleum (review), 629
structure of fields (review), 155
Porcupine district, vein structures, 103
Cannel coal, 382
boghead, torbanite, oil shale (Schopf), 68
Canton, Ohio, The utilization of induced stream infiltration and natural aquifer storage at (Kazmann), 514
Carbonate, 101
Carpenter, H. C. H., analysis by, 144
Carson, J. P., analysis by, 219
Carver, G. E., Jr., oil, Arcadia-Coon Creek pool, Okla. (review), 155
Cassiterite, 191, 235

Caviglia T. E., analyses by, 57
Cavinato, A., and Zuffardi, P., review of pamphlet by, 555
Central America, map (review), 458
Cerargyrite, 680
Cerro de Pasco, Peru, Geological explanation of geophysical anomalies near (Kruger and Lacy), 485
Cerussite, 39, 682
Chace, F. M., *Origin of the Bendigo saddle reefs with comments on the formation of ribbon quartz*, 561–597
abstract by, 83
Chalcedony, 15
Chalcocite, 39, 271, 469, 481, 683
Chalcopyrite, 37, 266, 320, 333, 469, 677, 678, 682, 698
Channels in the Albany-Schenectady area in New York, Buried preglacial ground water (Simpson), 713
Chapman, C. A., on quartz monzonite, 180
Chapman, T. L., on San Manuel deposit, Ariz., 254
Charmsbury, H. B., and Wright, C. C., on abietic acid, 652
Chase, E. C., and Bergsmark, D. R., review of book by, 556
Chaudron, G., and Forestier, H., on titanomagnetite, 223
Chemical analysis, chromite, 540
garnierite, Oregon, 18
glass sands, N. J., 66
gold, Dartmoor granite, England, 338
rocks and ores, Adirondacks, 219
slags, Ab Swayel mine, Egypt, 144
water, Azapa valley, Chile, 57
zinc in soils, Tenn., 290
Chemistry, coal, 6
ilmenite-hematite ore, Que., 736
zinc, tests, 296
Chile, Geology and ground water of the Azapa valley, Province of Tarapacá (Taylor), 40
China, Paikungshan coal field—A new discovery in the Huainan Basin, northern Anhui, central (Hsieh), 128
Chitarow, N. I., and Iwanow, L. A., on system H_2O—Na_2O—SiO_2, 744
Chlorite, 176, 439, 538, 571, 591
Chromite, 319
Chromite in New Caledonia, Some occurrences of (Maxwell), 525
Chrustschoff, K., on zircon, 721
Chrysocolla, 81, 254, 663, 701
Chrysotile, 541
Clarain, 379
Clark, G. B., on mining geology, 546
Clark, S. K., Arnett, C. L., and Royds, J. S., oil, Geneseo uplift, Kan. (review), 155
Clarke, F. W., on genthite, 22
Clastic ratio, 600
Clay mineral, 685, 686
Clays, alumina content of trees over clays, 451
Paikungshan coal field, China, 142
Cleavelandite, 326
Cloud, P. E., Jr., and Barnes, V. E., review of publication by, 555
Coal (review), 628
Electron microscopy of (McCartney), 617
research (abstract), 646
Texas (abstract), 638
United States (abstracts), 643, 646
Coal age, The new (Ashley), 161
Coal beds, Sedimentation: An appropriate field of research in the natural history of (Dapples), 598
Coal by the particle count method, Petrographic analysis of (Parks), 376
Coal field—A new discovery in the Huainan Basin, northern Anhui, central China, Paikungshan (Hsieh), 128
Coal geochemistry, The problems of (Miller), 649
Coal geology: An opportunity for research and study (Cady), 1
Coal paleobotany since 1943, Research in (Schopf), 492
Cobalt (review), 73
Gowganda, Ont., 438
Coeur d'Alene district, Idaho, Monzonite intrusion and mineralization in the (Anderson), 169
Collophanite, 141
Columbium, 235
Comb structure, 96
Comeforo, J. E., with Wilkerson, A. S., *Some glass sands from New Jersey*, 63–67
Communications—
Apparatus for the recording of decrepitation in minerals (Smith and Peach), 449
Examination of sands (Ries), 741
Higher alumina content of oak leaves and twigs growing over clay pits (Keller), 451
Laboratory testing of "pneumatolytic" deposits (Smith), 624
Sketchmaster for making geologic maps (Sohn), 551
Transport and deposition of the non-sulphide vein minerals. III. Phase relations at the pegmatitic stage (Smith), Morey, 151
Continents, submarine geology (review), 73
Cook, J. H., on buried channels, 717
Cook, J. H., and Ruedemann, R., on Albany area, N. Y., 716
Cooke, H. R., on book structure, 92
Cooke, S. R. B., and Perry, E. S., on columbium, 309
Cookson, I. C., on pollen, 506
Cope, F. W., on coal, 500

Copper, Arizona, Helvetia district (abstract), 639
San Manuel deposit (abstract), 81
Wallapai district, 663, 700
basic copper precipitation (abstract), 641
calculator for values, 445
California, Iron Mtn. (abstract), 82
Egypt, Ab Swayel mine, 143
interference with zinc tests, 302
replacement of wall rock (abstract), 642
Seventy Nine mine, Ariz., 38
Copper deposit, Arizona, Oxidation and enrichment in the San Manuel (Schwartz), 253
Correlation, subsurface methods (review), 746
Corundum, Montana, 314
Cosslett, V. E., on electron microscopy, 617
Cotton, C. A., review of book by, 630
Covellite, 39, 271, 473, 683
Cram, I. H., oil, Cumberland field, Okla. (review), 155
Crickmay, G. W., on Talladega series, 281
Crinkly bands, 583
Cross, A. T., on spores, 510
Crustification, 87, 578
Cuprite, 269, 683
Current, A. M., petroleum, Gilbertown field, Ala. (review), 155
Currier, L. W., on fluorite, 606
Cyclothem studies, 603

Dahllite, 141
Daly, R. A., on granite, 236
Dana, E. S., review of revised book by, 242
Dana, J. S., on genthite, 22
D'Ans, J., and Loffler, J., on $Na_2O.ZrO_2.1.5\ SiO_2$, 725
Dapples, E. C., *Sedimentation: An appropriate field of research in the natural history of coal beds*, 598–605
Darrah, W. C., on peel method, 617
on plants, 495
Davidson, D. M., review by, 347
Davison, E. H., on ores, Cornwall, England, 625
de Chetelat, E., on nickel, 526
Decrepitation apparatus for minerals, 449
Deformation, metamorphic rocks (review), 156
De Jersey, N. J., on spores, 505
De Jong, W. F., and Willems, H. W. V., on linnaeite, 148
Dendrite, silver, 440
Deposition, minerals, non-sulphide pegmatitic, 151
Deposition and resolution of native silver at Gowganda, Ontario, (Bastin), 437
Deposition of the non-sulphide vein minerals. IV. Tourmaline. Transport and (Smith), 186
V. Zirconium minerals, Transport and (Maurice), 721
Desch, G. H., analysis by, 144
Determination of reflectivity of the ore minerals (Folinsbee), 425
Determination of zinc in soils, Field method for the (Lakin, Stevens, and Almond), 296
Device for calculating stoping values from assays of narrow veins (Kruger), 445
Deville, S.-C., on zircon, 721
Deweylite, 20
Diagrams—
assay slide rule, 446
bedrock topography, Albany, N. Y., 716
chromite in workings, New Caledonia, 528
coal molecule, 654
corundum with baddeleyite, 315
decrepitation curve for amblygonite, 450
feeding device for sluice, 195
fluorite mineralization, Ill., 612
fracture directions, Seventy Nine mine, Ariz., 35
garnierite, analyses, 19
lithofacies triangle, 599
paragenesis, monzonites, Coeur d'Alene, Idaho, 179
ores, Seventy Nine mine, Ariz., 38
silver, Gowganda, Ont., 443
Wallapai district, Ariz., 676
petrographic analysis of coals, 388
polishing apparatus, 125
ribbon quartz in veins, 96
saddle reefs, Bendigo, Australia, 563
sheeted terrane and ground water, 113
sketchmaster, 552
spores in coals, England, 500
system H_2O—Na_2O—SiO_2, 743
titania and iron oxides, 214
tourmaline and albite relations, 190
two-liquid relations, 153
veins, perpendiculars to veins, Wallapai, Ariz., 675
water recharge collector, Ohio, 521
Diamonds (review), 628
Diaspore, 137, 453
Dickite, 687
Differentiation of titaniferous magmas (Evrard), 210
Digenite, 470, 481
Dijkstra, S. J., on Triletes, 509
Dikes, Arizona, Helvetia district (abstract), 640
Wallapai district, 666, 694
Bendigo district, Australia, 569
chromite deposits, New Caledonia, 542
pegmatites, Montana, 307
porphyritization, 341
San Manuel district, Ariz., 256
Seventy Nine mine, Ariz., 28, 33
Diller, J. S., and Kay, G. F., on Riddle district, Ore., 14
Discussions—
Liquid immiscibility in hydrous silicate systems (Morey), Friedman, 742

Discussions—Continued
Mineral relationships in the ores of Pachuca and Real del Monte, Hidalgo, Mexico (Bastin), (Wisser), Geyne, 233
Ore and granitization (Sullivan), 336; Garretty, 625
Transport and deposition of pegmatite minerals (Morey), Smith, 741
Transport and deposition of the non-sulphide vein minerals. III. (Ramberg), 551
Dithizone, 342
Dorn, P., on plants, 709
"Dornicks," Shelby Co., Ala., 278
Dorr, J. V. N., II, and Guild, P. W., abstract by, 646
Dougherty, E. Y., on book structure, 92
Dresser, J. A., on chromite, 540
Dreyer, R. M., Howland, A. L., and Garrels, R. M., abstract by, 642
Drilling (review), 348
Paikungshan coal field, China, 134
Dulhunty, J. A., on microfossils, 504
Dunbar, C. O., review of book by, 243
Dunite, 15
New Caledonia, 528
Dunn, E. J., on Bendigo goldfield, Australia, 568
Dunn, J. A., on porphyries, 342
on silicates, 318
Durain, 380

Ebbutt, F., gold, deposition and structures, Canada (review), 72
on gold, 594
Eckel, E. B., on water, 623
Eckel, E. C., on brown ores, 283
Education, Mining geologists, 358, 548
Edwards, A. B., and Gaskin, A. J., discussion by, 234
discussion of reply by, 336
Egypt, The discovery of nickel in (*Nassim*), 143
Eisenack, A., on plants, 495
Electric power, United States, consumption, 162
Elias, M. K., on Big Blue sediments, Kans., 602
Ellestad, R. B., analyses by, 220
Ellis, E. E., on joints, 116
Ellis, H. A., on pegmatites, 342
Ellison, S. P., Jr., oil, Apco field, Texas (review), 155
Elovskaya, M. V., on spores, 497
Elsing, M. J., and Heineman, R. E. S., on Golconda mine, Ariz., 672
Emmons, W. H., on chalcocite, 274
on mineralization, 344, 694, 695
on ore deposits, 241
on oxidation, 38
on pegmatites, 308
Enargite, 469
Engel, A. E. J., abstract by, 79
Engineering aspects of mineral exploration, Mining geology and the (Forrester), 545
England, tin, Cornwall, 624
English, R. M., and Grogan, R. M., oil, Omaha pool, Ill. (review), 155
Enrichment, Arizona, San Manuel copper deposit (abstract), 81
Seventy Nine mine, Ariz., 38
Wallapai district, Ariz., 684, 699
Enrichment in the San Manuel copper deposit, Arizona, Oxidation and (Schwartz), 253
Enstatite, 533
Eocene age in Fayette County, Tennessee, A hypothesis on the origin of a limonitic layer in beds of (Schneider), 621
Epidote, 176, 324, 488, 490
Erdtman, G., on spores, 505
Ettlinger, I. A., on Central Arizona batholith, 29
Evrard, P., *The differentiation of titaniferous magmas*, 210–232
analyses by, 219
on titaniferous ores, 212, 228
Experiments, coal, petrographic analysis, 383
heavy mineral concentration, 197
zirconium minerals, stability, 722
Exploration, Mining geology and the engineering aspects of mineral (Forrester), 545
Exploration for ore deposits (Broderick), 357

Factor of regularity, 165
Farmin, R., on ribbon structure, 92, 562
Faults, Arizona, Helvetia district (abstract), 640
San Manuel area, 258
Wallapai district, 663, 670, 696
Bendigo district, Australia, 569, 593
California, Cerro Gordo area (abstract), 82
Cave in Rock district, Ill., 607
Coeur d'Alene district, Idaho, 170
Seventy Nine mine, Ariz., 27, 29
Shelby district, Ala., 279
Faust, G. T., thermal analysis by, 20
Ferguson, H. G., on ore deposits, 456
review by, 455
Ferguson, H. G., and Gannett, R. W., on crinkly bands, 575
on ribbon structure, 89, 92
Fergusonite, 313
Fersman, A. E., on spectrographs, 709
Field method for the determination of zinc in soils (Lakin, Stevens, and Almond), 296
Finucane, K. J., Sullivan, C. J., and Telford, R. J., on chrysotile, 340
Fischer, F., on coal, 653
Fischer, H., and Leopoldi, G., on dithizone, 297
Fisher, L. W., on chromite, 527

Fix, P. F., title by, 84
Flare, correction for, 426
Flerov, B. L., on tin, 708
Flinders, W. F., on slag, 149
Fluorite, 679
Fluorspar deposits of southern Illinois, Structures due to volume shrinkage in the bedding-replacement (Grogan), 606
Folds, Bendigo district, Australia, 83, 569
Folinsbee, R. E., *Determination of reflectivity of the ore minerals*, 425–436
Ford, W. E., on chrysocolla, 701
Formation of ribbon quartz, Origin of the Bendigo saddle reefs with comments on the (Chace), 561
Formulas, Gladstone and Dale, index of refraction, 20
Forrester, J. D., *Mining geology and the engineering aspects of mineral exploration*, 545–550
  on copper, 708
Fortier, Y. O., on chromite, 538
Fractures, Seventy Nine mine, Ariz., 35
Fresnel equation, 427, 429
Friedensburg, F., review of book by, 243
Friedman, I., discussion by, 742
Frondel, C., Hurlbut, C. S., Jr., and Collette, R. C., on tourmaline, 187
Fouqué, F., and Lévy, M., on tourmaline, 187
Fuchs, W., on coal, 657
Fuchs, W., and Daur, R., on coal, 656
Furcron, A. S., on ground water, 111
Fusain, 6, 380, 387
Fusinite, 6

Galena, 37, 239, 607, 677, 682, 698
Gallagher, D., on gold, 340
Garnet, 176, 324
Garnier, J., on chromite, 527
  on mineral, 22
Garnierite from the nickel deposit near Riddle, Oregon, Variations in (Pecora, Hobbs, and Murata), 13
Garrels, R. M., Howland, A. L., and Dreyer, R. M., abstract by, 641
Garrett, S. K., on zoning, 692
Garretty, M. D., discussion by, 625
Geer, M. R., and Yancey, H. F., on coal, 406
Genesis, monzonites, Coeur d'Alene, Idaho, 178
  ore deposits, Coeur d'Alene district, Idaho, 169
  ores, Wallapai district, Ariz., 694, 699, 702
  zirconium minerals, 729
Genth, F. A., on nickel gymnite, 22
Genthite, 22
Geochemical prospecting for ores: A progress report (Hawkes), 706; abstract, 80
Geochemistry (review), 457
  The problems of coal (Miller), 649
Geography (review), 556
Geological explanation of geophysical anomalies near Cerro de Pasco, Peru (Kruger and Lacy), 485
Geological maps, Adirondacks, titaniferous deposits, 211
  Arizona, Chloride district, 669
    San Manuel area, Ariz., 257
    Seventy Nine mine, Ariz., 26
  Azapa valley, Chile, 42
  Canton area, Ohio, 515
  Cave in Rock fluorite deposits, Ill., 607
  Huainan Basin, China, 131
  preparation by sketchmaster (communication), 551
  Shelby district, Ala., 279
  Venencocha area, Peru, 486
Geologists, education and training, 358
Geology, Allard Lake district, Quebec, 733
  Arizona, Helvetia district (abstract), 639
    San Manuel copper deposit, 255
    Wallapai district, 668
  Azapa valley, Chile, 45
  Bendigo, Australia, 83, 568
  California, Bishop tungsten district (abstract), 79
    Cerro Gordo area (abstract), 82
    Iron Mtn. sulphide deposits (abstract), 81
  Friends Station area, Tenn., 286
  historical geology (review), 243, 555
  Idaho, Cache valley (by title), 84
  mining (reviews), 347, 745
  Nevada, Goldfield (review), 455
  New Caledonia, 526
  ore deposits (review), 628
  petroleum (review), 242
  physical geology (review), 72
  Quaternary deposits, Canton, Ohio, 514
  Riddle garnierite deposit, Oregon, 14
  Seventy Nine mine, Ariz., 27
  Shelby district, Ala., 279
  submarine geology (review), 73
  Venencocha area, Peru, 486
Geology: An opportunity for research and study, Coal (Cady), 1
Geology and ground water of the Azapa valley, Province of Tarapacá, Chile (Taylor), 40
Geology and man (reviews), 352
Geology and the engineering aspects of mineral exploration, Mining (Forrester), 545
Geophysical anomalies near Cerro de Pasco, Peru, Geological explanation of (Kruger and Lacy), 485
Geophysical prospecting (review), 348
  Goldfield, Nev. (review), 455
  textbook (review), 458
Geophysics, heat conduction (review), 352
  subsurface methods (review), 746
Georgia, Sheet structure a major factor in in the occurrence of ground water in the granites of (LeGrand), 110
  limonitic ores, 284

Germany, linnaeite, x-ray study, 148
Geyne, A. R., discussion by, 233
Gill, J. E., pre-Cambrian Shield, Canada (review), 72
Gillson, J. L., on quartz monzonite, 179
on sphene, 687
Gilluly, J., on Ajo area, Ariz., 275
on granite, 338
Gladstone and Dale formula, 20
Glass sands from New Jersey, Some (Wilkerson and Comeforo), 63
Glasser, E., on chromite, 527
on mineral deposits, New Caledonia, 526
Goethite, 269, 273
Gold, 89, 561, 572, 592, 678, 683
calculator for values, 445
California, Mother Lode region (review), 74
England, Dartmoor granite, 338
Nevada, Goldfield area (review), 455
substitution for other elements, 237
Gold-quartz veins, Ribbon structure in (McKinstry and Ohle), 87
Goranson, R. W., on vermiculite, 333
on water, 151
Gordon, M., Jr., Tracey, J. I., Jr., and Ellis, M. W., abstract by, 640
Gossans, Cerro de Pasco, Peru, 488
geochemical prospecting, 708
Wallapai district, Ariz., 683
Gottlieb, E., on amino acids, 658
Gouge, 692
Gowganda, Ontario, Deposition and resolution of native silver at (Bastin), 437
Granites of Georgia, Sheet structure, a major factor in the occurrence of ground water in the (LeGrand), 110
Granitization and ore (discussions), 234, 336, 625
Graphic granite, 320
Graphite, 318, 326, 329
Graphitic slips, 584
Graphs, aeromagnetic profile, Allard Lake, Que., 737
coal, banded ingredients, 396
garnierite, analyses and dehydration, 19
reflectivities of ore minerals, 428
Sandy Creek flow, Ohio, 516
scours, logarithmic relationships, 203
springs, and galleries, discharge, Azapa valley, Chile, 55
ZrO_2—SiO_2—Na_2O phase relations, 724
Graton, L. C., on ore genesis, 345
on quartz, 690
on solutions, 468, 477
Graton, L. C., and Bowditch, S. I., on alteration, 687
on alunite, 488
Graton, L. C., *et al.*, on quartz, 101
Greenland, map (review), 458
Griggs, D., on carbonate, 102
Grogan, R. M., *Structures due to volume shrinkage in the bedding-replacement fluorspar deposits of southern Illinois*, 606–616
Ground water channels in the Albany-Schenectady area in New York, Buried preglacial (Simpson), 713
Ground water in the granites of Georgia, Sheet structure, a major factor in the occurrence of (LeGrand), 110
Ground water of the Azapa valley, Province of Tarapacá, Chile, Geology and (Taylor), 40
Grout, F. F., on carbonates, 102
on dikes, 695
Gruner, J. W., on feldspar, 730
on vermiculite, 333
Guild, F. N., on galena, 37
Gustafson, J. K., and Miller, F. S., on domes, 343

Hagen, E., and Rubens, H., on silver, 431
Harder, E. C., on water, 623
Harris, W. J., and Thomas, D. E., on goldfields, 343
Haury, P. S., on Tennessee-Schuylkill mine, Ariz., 672
Hautefeuille, P., and Perry, A., on zircon, 721
Hawkes, H. E., *Geochemical prospecting for ores: A progress report*, 706–712; abstract, 80
on prospecting, 707
Hawkes, H. E., and Lakin, H. W., *Vestigial zinc in surface residuum associated with primary zinc ore in east Tennessee*, 286–295
on zinc, 296, 708
Hawley, L. F., and Harris, E. E., on lignin, 656
Heavy minerals in coal, 388
Hedström, H., and Nordström, A., on plant ash, 709
Heinrich, E. W., *Pegmatites of Montana*, 307–335
on granite, 310
on kyanite, 317
Helfinstine, R. J., and Boley, C. C., on coal, 379
Hematite, 221, 646, 735
Herman, H., on Bendigo goldfield, Australia, 568
Hernon, R. M., on Wallapai district, Ariz., 664
Hillebrand, W. F., analyses by, 220
Hillebrand, W. F., and Lundell, G. E. F., on zinc, 297
History, Ab Swayel copper mine, Egypt, 143
mining, U. S., World War II (review), 629
Hitchen, C. S., on serpentine, 540

Hobbs, S. W., with Pecora, W. T., and Murata, K. J., *Variations in garnierite from the nickel deposit near Riddle, Oregon*, 13–23
Holland, T. H., on corundum, 317
Holmes, R. S., on zinc, 292, 296, 303
Hopkins, J. B., and Taber, J., on corundum, 314
Hornblende, 173, 331
Howard, H. C., on coal, 650
on humic acids, 651
Howe, E., on book structure, 92
Howell, J. V., review of book edited by, 155
Hsieh, C. Y., *Paikungshan coal field—A new discovery in the Huainan Basin, northern Anhui, central China*, 128–142
Huff, L. C., on metals, 708
Hughes, D. S., and Pondrom, W. L., on magnetic components, 737
Hulin, C. D., on book structure, 91
on dikes, 695
on mineralization, 341
on ribbon structure, 562
Hume, W. F., on Ab Swayel mine, Egypt, 144
Humic acids, 651
Hurlbut, C. S., Jr., review of book revision by, 242
Hurst, M. E., on book structure, 91
on ribbon structure, 562
Hydrology (review), 746

Idaho, Monzonite intrusion and mineralization in the Coeur d'Alene district (Anderson), 169
ground water, Cache Valley (by title), 84
Illinois, Structures due to volume shrinkage in the bedding-replacement fluorspar deposits of southern (Grogan), 606
coal petrographic analysis, 379
cyclothem, Pennsylvanian, 603
Ilmenite, 221, 734
Inclusions, liquid inclusions in pneumatolytic deposits, 624
Indonesia, thorium, 235
Infiltration and natural aquifer storage at Canton, Ohio, The utilization of induced stream (Kazmann), 514
Infiltration galleries, Azapa valley, Chile, 54
Ingersoll, L. R., Zobel, O. J., and Ingersoll, A. C., review of book by, 352
Intrusion and mineralization in the Coeur d'Alene district, Idaho, Monzonite (Anderson), 169
Iron, Alabama, limonite, Shelby Co., 278
Brazil, Minas Gerais (abstract), 646
limonite, Eocene, Tenn., 621
Irrigation, water, safe and unsafe, 59
"Island" textures, bornite, 475
Italy, lead and zinc, Montevecchio (review), 555
Iuneev, M. V., on copper, 708

Jaffe, H. W., on sphene, 687
Jahns, R. H., on granite, 113
Japan, ore deposits (discussion), 240
Jenkins, O. P., review of guidebook by, 74
Jensen, H. I., on Miocene, New Caledonia, 527
Johnson, V. H., abstract by, 639
Johnston, G. R., on pegmatites, 323
Johnston, W. D., Jr., on book structure, 91
on quartz, 577
on ribbon structure, 562
Joints, Arizona, Wallapai district, 668
Jones, V., on chromite, 330
Jouravsky, G., on titanomagnetites, 223
Juettner, B., and Howard, H. C., on coal, 652
Junner, R. N., on titanomagnetite, 225

Kaolinite, 453
Kay, G. F., on Riddle district, Ore., 14
Kayser, E., review of book by, 555
Kazmann, R. G., *The utilization of induced stream infiltration and natural aquifer storage at Canton, Ohio*, 514–524; abstract, 84
Keller R., C., on rainfall, Arica, Chile, 43
Keller, W. D., communication by, 451
on clays, 453
Kellogg, C. E., on soils, 287
Kemp, J. F., on iron, 222
Kemp, J. F., and Ruedemann, R., on gabbro, 229
Kiersch, G. A., *Structural control and mineralization at the Seventy Nine mine, Gila County, Arizona*, 24–39
Kinkel, A. R., Jr., and Albers, J. P., abstract by, 81
Knechtel, M. M., on Gila conglomerate, Ariz., 28
Knight, C. W., on granite, 340
Knight, W. C., analysis by, 219
Knopf, A., on book structure, 91
on boron, 321
review by, 457
Knox, E. M., on spores, 499
Koehne, W., review of book by, 458
Kosanke, R. M., abstract by, 646
on plants, 510
on spores, 4
Kreiter, V. M., on copper, 708
Krieger, P., on manganocalcite, 679
Kruger, F. C., *A device for calculating stoping values from assays of narrow veins*, 445–448
Kruger, F. C., and Lacy, W. C., *Geological explanation of geophysical anomalies near Cerro de Pasco, Peru*, 485–491
Krumbein, W. C., on sediments, 600
Krynine, P. D., on sediments, 600
on tourmaline, 191
Kutina, J., abstract by, 642
Kyanite, 317

Lacroix, A., on garnierite, 22
on norite, 527
Lacy, W. C., with Kruger, F. C., *Geological explanation of geophysical anomalies near Cerro de Pasco, Peru*, 485–491
Lakin, H. W., Stevens, R. E., and Almond, H., *Field method for the determination of zinc in soils*, 296–306
on zinc, 286, 709
Lakin, H. W., with Hawkes, H. E., *Vestigial zinc in surface residuum associated with primary zinc ore in east Tennessee*, 286–295
Lalicker, C. G., review of book by, 242
Landes, K. K., abstract by, 641
oil, Deep River field, Mich. (review), 155
on pegmatites, 309
review of book by, 352
Landes, K. K., and Hussey, R. C., review of book by, 352
Landscapes (review), 630
Lang, A. H., Cordilleran region, Canada (review), 72
Lang, W. H., and Cookson, I. C., on plants, 495
Laps, for polishing sections, 120
Larsen, E. S., and Berman, H., on index of refraction, 20
on minerals, 431
Larsen, E. S., and Hunt, W. F., on vermiculite, 333
Larsen, E. S., and Pardee, J. T., on vermiculite, 333
Lasky, S. G., abstract by, 82
Lawrence, B. B., on mineral exploration, 545
Leach, C. E., petroleum, Aliso Canyon field, Calif. (review), 155
Leach, P., on water, 709
Lead, Arizona, Wallapai district, 663
California, Cerro Gordo mine (abstract), 82
genesis of deposits (communication), 626
interference with zinc tests, 302
Italy, Montevecchio (review), 555
Mexico (abstract), 639
Pachuca district (discussion), 233
Seventy Nine mine, Ariz., 32, 36
Washington, Northport district (abstract), 639
Lee, W. T., on extrusives, 667
LeGrand, H. E., *Sheet structure, a major factor in the occurrence of ground water in the granites of Georgia*, 110–118
Legraye, M., on titanomagnetite, 225
Leighton, M. M., reviews by, 351, 745
Lenher, J., and Merril, H. B., on silica, 728
Lenny, D. B., analysis by, 66
Lepidolite, 326
LeRoy, L. W., and Crain, H. M., review of symposium edited by, 746
Leverin, H. A., analysis by, 219
Lidgey, E., on plants, 709
Lignite, Canada (abstract), 644
North Dakota (abstract), 644
United States (abstracts), 643, 645
Vermont, Brandon (abstract), 645
Limestones, 602
United States, metallurgical reserves (abstract), 641
"vaughanitic," Ala., 278
Limonite, 38, 681
Limonite ores, A suggested origin for the Shelby County, Alabama (Allen), 278
Limonitic layer in beds of Eocene age in Fayette County, Tennessee, A hypothesis on the origin of a (Schneider), 621
Lindberg, G. D., oil, Deerfield pool, Mich. (review), 155
Lindgren, W., on ankerite, 578
on mineral exploration, 545
on ore deposits, 39
on pyrite, 677
on quartz, 97, 690
on replacement, 581
on ribbon structure, 88, 93
on slate, 592
on veins, 344
Linforth, F. A., on mineral exploration, 545
Linnaeite, x-ray study, Westphalia, Germany, 148
Linstow, O. V., on plants, 709
Liversidge, A., on noumeite, 22
Lobeck, A. K., on exfoliation, 114
Locke, A., on dacite, 455
on gangues, 681
on gossans, 708
Locke, A., Hall, D. A., and Short, M. N., on textures, 472
Logarithmic pattern in river placer deposits (Wertz), 193
Lollingite, 442
Longwell, C. R., Knopf, A., and Flint, R. F., review of book by, 72
Loughlin, G. F., on dikes, 695
Lovering, T. S., on argillized material, 33
on copper, 708
on pegmatites, 332
on San Manuel district, Ariz., 254
Lovering, T. S., Sokoloff, V. P., and Morris, H. T., on metallogenetic provinces, 338
Lowe, E. N., on Eocene, Miss., 622
Lowenstam, H. A., oil, Marine pool, Ill. (review), 155
Lowry, H. H., on coal, 8, 652
Luber, A. A., on microfossils, 499
Luber, A. A., and Waltz, I. E., on spores, 497
Lundberg, H., on vegetation, 709
Lungwitz, E. E., on gold, 709

McCabe, L. C., on coal, 384
on vitrain, 381
McCabe, L. C., and Quirke, T. T., on vitrain, 659
McCabe, L. C., Mitchell, D. R., and Cady, G. H., on coal, 382
McCallie, S. W., on limonite, 284
McCartney, J. T., *Electron microscopy of coal*, 617–620
Macerals, 494
MacKay, B. R., abstract by, 644
McKinstry, H. E., on Bendigo goldfield, Australia, 568
on fissures, 693
on fractures, 575
on mining geology, 546
on openings, 596
review of book by, 347
McKinstry, H. E., and Ohle, E. L., Jr., *Ribbon structure in gold-quartz veins*, 87–109
on ribbon structure, 562
Maclaren, J. M., on gold, 338
McMasters, J. H., petroleum, Cymric field, Calif. (review), 155
McQueen, H. S., on clay, 453
Magmas, The differentiation of titaniferous (Evrard), 210
Magmas and ore genesis (review), 554
Magnetite, 176, 195, 239, 529, 539, 735
Maguire, D., on quartz, 320
Maillard, L. C., on amino acids, 658
Malaya, monazite and tantalite, 336
thorium, 235
Maliuga, D. P., on copper, 708
Malyshev, I. I., on titaniferous ores, 223
Malyshev, I. I., Panteleev, P. G., and Pek, A. V., on titaniferous ores, 223
Manganocalcite, 679
Manitoba, amblygonite, decrepitation, 450
Maps, Alabama, Shelby area, 279
Allard Lake district, Quebec, 733
Americas (review), 458
Arizona, Chloride Quadrangle, 665
buried channels, Schenectady region, N. Y., 715
China, Huainan coal fields, 129
Coeur d'Alene, Idaho, 170
Illinois, coal, samples for analysis, 399
New Caledonia, 526
New Jersey, glass sands, 64
Oregon, Riddle district, 14
sluice deposits, 196
Marcasite, 333, 677
Matheson, R. S., and Hobson, R. A., on pegmatites, 342
Maurice, O. D., *Transport and desposition of the non-sulphide vein minerals. V. Zirconium minerals*, 721–731
Maxwell, J. C., *Some occurrences of chromite in New Caledonia*, 525–544
Maynard, —., analyses by, 221
Mead, W. J., on dilatancy, 583
Meinzer, O. E., memorial, 248
Memorial, Meinzer, O. E., 248
Menzel, A., on humic acids, 651
Mercury, interference with zinc tests, 302
Texas, Terlingua district (abstract), 640
Merriam, C. W., abstract by 82
Merwin, H. E., and Lombard, R. H., on sulphides, 476
Metallogenetic provinces, 337
Mexico (abstract), 638
Metals, interference with tests for zinc, 302
Metamorphic rocks, mineralogy and structure (review), 155
Metamorphism, California, Bishop district (abstract), 79
Coeur d'Alene, Idaho, 180
Metasomatism in metamorphism (review), 156
Method, Petrographic analysis of coal by the particle count (Parks), 376
Method for polishing sections of ores (Sampson), 119
Method for the determination of zinc in soils, Field (Lakin, Stevens, and Almond), 296
Mexico, ore deposition patterns (abstract), 638
ores, Pachuca (discussion), 233
petroleum (review), 629
Meyer, C., with Sales, R. H., *Results from preliminary studies of vein formation at Butte, Montana*, 465–484
Mica, Montana, 308
Mich. Mine Appraisal System (review), 459
Micrinite, 6
Microbrecciation and microfractures, 594
Microcline, 174, 320, 323, 326
Micropaleophytology, 494
Microscopy, electron microscopy, coal, 617
Microscopy of coal, Electron (McCartney), 617
Microvitrain, 379, 384, 386, 423
Mignone, M. L., books received, 556, 630
reviews by, 555, 628, 629
Mikesell, R. F., and Chenery, H. B., review of book by, 351
Miller, H. P., *The problems of coal geochemistry*, 649–662
Miller, R. L., oil, Rose Hill field, Va. (review), 155
Miller, W. G., on corundum, 317
Miller, W. J., on metagabbro, 229
Millott, J. O'N., on spores, 501
Mimetite, 681
Mineral charcoal, 382
Mineral exploration, Mining geology and the engineering aspects of (Forrester), 545
Mineral industry (review), 243
Mineralization, Broken Hill, New South Wales, 626
copper, San Manuel area, Ariz., 261
gold, Nevada, Goldfield area (review), 455
Mexico (abstract), 638
ore genesis (communication), 554

Mineralization—Continued
Seventy Nine mine, Ariz., 32
tin, pneumatolytic deposits, 624
Wallapai district, Ariz., 663, 698
Mineralization at the Seventy Nine mine, Gila County, Arizona, Structural control and (Kiersch), 24
Mineralization in the Coeur d'Alene district, Idaho, Monzonite intrusion and (Anderson), 169
Mineralogy (review), 242
Arkansas, Ouachita mineral province (abstract), 79
Bendigo goldfield, Australia, 571
copper-iron-sulphur minerals, 476
garnierite, Riddle, Ore., 17
Klockmann's mineralogy (review), 351
metamorphic rocks (review), 155
monzonites, Coeur d'Alene, Idaho, 172
ores, Ab Swayel mine, Egypt, 144
ilmenite-hematite, Que., 736
ores and gangue, Wallapai district, Ariz., 673, 680
sands (communication), 741
silver ores, Gowganda area, Ont., 438
Minerals, Determination of reflectivity of the ore (Folinsbee), 425
IV. Tourmaline. Transport and deposition of the non-sulphide vein (Smith), 186
V. Zirconium minerals, Transport and deposition of the non-sulphide vein (Maurice), 721
decrepitation apparatus, 449
glass sands, N. J., 65
paragenesis, accessory minerals in igneous rocks (abstract), 642
pegmatites, transport and deposition (discussion), 551, 741
Mines, Michigan appraisal system (review), 459
Mines Register (review), 746
Mining, Ab Swayel mine, Egypt, 146
U. S., World War II (review), 629
Mining geology (review), 745
subsurface methods (review), 746
Mining geology and the engineering aspects of mineral exploration (Forrester), 545
Missouri, alumina in tree ash over clays, 451
Mitchelson, A. T., and Muckel, D. C., on water, 61
Molybdenite, 320, 698
Molybdenum, Arizona, Helvetia district (abstract), 640
Monazite, 235, 336
Monroe, W. H., Conant, L. C., and Eargle, D. H., on limonite, 621
Montana, Pegmatites of (Heinrich), 307
Results from preliminary studies of vein formation at Butte (Sales and Meyer), 465
Montgomery, A., on silver, 440
Monzonite intrusion and mineralization in the Coeur d'Alene district, Idaho (Anderson), 169
Moon, J. W., *et al.*, on soil, 289
Moore, L. R., on spores, 502
Moorhouse, W. W., Peach, P. A., and Buchanan, R. M., abstract by, 642
Moraes, L. J. de, on hydrosilicate, 22
Morey, G. W., discussion by, 151
on K_2O—SiO_2—H_2O system, 743
reviews of discussion by, 741, 742
Morey, G. W., and Fenner, C. N., on silicates, 727
Morgan, J. D., Jr., review of book by, 629
Morley, E. W., analysis by, 220
Morozewicz, J., on corundum, 317
Mundorff, M. J., on ground water, 111, 117
Muñoz C., J., on Jurassic fossils, 48
Muñoz Cristi, J., and Flores Williams, H., on Liparitic formation, Chile, 45
Murata, K. J., analyses, by, 18
Murata, K. J., with Pecora, W. T., and Hobbs, S. W., *Variations in garnierite from the nickel deposit near Riddle, Oregon*, 13–23
Muscovite, 313, 325

Nacrite, 687
Nassim, G. I., *The discovery of nickel in Egypt*, 143–150
Native copper, 272, 333
Native silver, 439, 683
Native silver at Gowganda, Ontario, Deposition and resolution of (Bastin), 437
Natural gas, United States, consumption, 162
Naumova, S. N., on spores, 497
Nevada, ore deposits, Goldfield (review), 455
New Caledonia, Some occurrences of chromite in (Maxwell), 525
New Jersey, Some glass sands from (Wilkerson and Comeforo), 63
New South Wales, Broken Hill ore deposit (discussion), 626
New York, Buried preglacial ground water channels in the Albany-Schenectady (Simpson), 713
titaniferous deposits, 210
Newhouse, W. H., on openings, 580
Nickel, genesis by granites, 340
Gowganda, Ont., 438
interference with zinc tests, 302
substitution for other elements, 237
Nickel deposit near Riddle, Oregon, Variations in garnierite from the (Pecora, Hobbs, and Murata), 13
Nickel gymnite, 22
Nickel in Egypt, The discovery of (Nassim), 143
Nigeria, tantalum and tin, 235
Niggemann, H., on humic acids, 651
Niggli, P., on metallogenesis, 337
review of book by, 457
Noble, J. A., review by, 554

Noble, J. A., Harder, J. O., and Slaughter, A. L., on dilatation, 583
Noé, A. C., on coal balls, 4
Nolan, T. B., on ore deposits, 456
on zoning, 455
North Dakota, lignite (abstract), 644
Noumeite, 22
Nutting, P. G., dehydration curve by, 21

O'Brien, R. D., on corundum, 314
O'Brien, R. D., and Taber, J., on corundum, 314
Occurrences of chromite in New Caledonia (Maxwell), 525
Oceans, geology (review), 73
Ohio, The utilization of induced stream infiltration and natural aquifer storage at Canton (Kazmann), 514; abstract, 84
Ohle, E. L., Jr., with McKinstry, H. E., *Ribbon structure in gold-quartz veins*, 87–109
Oil shale, Cannel, boghead, torbanite (Schopf), 68
Olivine, 530
Ontario, Deposition and resolution of native silver at Gowganda (Bastin), 437
nickel, genesis, Sudbury, 340
Orcel, J., reflectivity determination, 431
Ore and granitization, 234, 336, 625
Ore bodies, Allard Lake district, Que., 739
Ore deposits (review), 628
Exploration for (Broderick), 357
Allard Lake district, Que., 735
California, Mother Lode region (review), 74
Canada, structure (review), 72
Coeur d'Alene, Idaho, 181
copper, San Manuel area, Ariz., 259
epithermal deposits, origin (abstract), 641
genesis (review), 554
gold, Bendigo district, Australia, 83, 568
granitization and ore, 234
lead-zinc, Italy, Montevecchio (reviews), 555
Mexico (abstract), 638
Nevada, Goldfield (review), 455
pneumatolytic deposits, 624
prospecting and thermal springs (abstract), 83
Seventy Nine mine, Ariz., 32
textbook (review), 457
tin, genesis (discussion), 626
tungsten, California, Bishop district (abstract), 79
veins, chemistry and spectroscopy (abstract), 642
Ore deposits and rocks (reviews), 457
Ore deposits of the Wallapai district, Arizona (Thomas), 663
Ore in east Tennessee, Vestigial zinc in surface residuum associated with primary (Hawkes and Lakin), 286
Ore minerals, Determination of reflectivity of the (Folinsbee), 425
Ore shoots, copper, Butte, Mont., 469
Wallapai district, Ariz., 692
Oregon, Variations in garnierite from the nickel deposit near Riddle (Pecora, Hobbs, and Murata), 13
Ores, A method for polishing sections of (Sampson), 119
A progress report, Geochemical prospecting for (Hawkes), 706
A suggested origin for the Shelby County, Alabama, limonite (Allen), 278
calculator for stoping values, 445
chromite, New Caledonia, 525, 528
genesis (review), 554
geochemical prospecting (abstract), 80
lead-zinc, Mexico, Pachuca (discussion), 233
search and appraisal (review), 349
Seventy Nine mine, Ariz., 34
titaniferous magnetites and gabbros, 217
Wallapai district, Ariz., 673
Origin, book structure, 91
chromite, New Caledonia, 541
epithermal deposits (abstract), 641
garnierite, Riddle, Ore., 17
mercury, Terlingua district, Texas (abstract), 640
ribbon structure, 93
sheeting in granites, Ga., 113
turquoise, Wallapai district, Ariz., 700
Origin for the Shelby County, Alabama, limonite ores, A suggested (Allen), 278
Origin of a limonitic layer in beds of Eocene age in Fayette County, Tennessee, A hypothesis on the (Schneider), 621
Origin of the Bendigo saddle reefs with comments on the formation of ribbon quartz (Chace), 561
Orthoclase, 174, 551
Osborne, F. F., on ilmenite, 229
Oxidation, Arizona, San Manuel copper deposit (abstract), 81
Seventy Nine mine, Ariz., 38
Wallapai district, Ariz., 680, 699
coal, 651
Oxidation and enrichment in the San Manuel copper deposit, Arizona (Schwartz), 253

Paige, S., on turquoise, 700
Paikungshan coal field—A new discovery in the Huainan Basin, northern Anhui, central China (Hsieh), 128
Palache, C., Berman, H., and Frondel, C., on minerals, 431
Paleobotany since 1943, Research in coal (Schopf), 492
Palmunen, M. K., analysis by, 219
on ilmenite, 225

Paragenesis, accessory minerals in igneous rocks (abstract), 642
monzonite, minerals, 176
ores, silver, Gowganda, Ont., 443
Seventy Nine mine, Ariz., 37
Wallapai district, Ariz., 673
Pardee, F. G., on mine appraisal (review), 459
Pardee, J. T., and Larsen, E. S., on vermiculite, 309
Park, C. F., on chalcopyrite, 479
Parks, B. C., *Petrographic analysis of coal by the particle count method*, 376–424
abstract by, 645
on coal, 6
Parks, R. D., review of book by, 459
Parry, V. F., abstract by, 643
Particle count method, Petrographic analysis of coal by the (Parks), 376
Peacock, H., on mineralization, 694
Pecora, W. T., on garnierite, 22
on minerals, 332
on pegmatites, 309, 332
Pecora, W. T., and Hobbs, S. W., on Riddle district, Oregon, 14
Pecora, W. T., Hobbs, S. W., and Murata, K. J., *Variations in garnierite from the nickel deposit near Riddle, Oregon*, 13–23
Peele, R., *et al.*, on mineral exploration, 545
Pegmatites, minerals, transport and deposition, 151; (discussions), 551, 741
pyroxenite, New Caledonia, 533
tourmaline deposition, 191
zirconium minerals, 729
Pegmatites of Montana (Heinrich), 307
Penfield, S. L., and Foote, H. W., on tourmaline, 186
Pennebaker, E. N., on brecciation, 696
Peoples, J. W., and Howland, A. L., on pegmatites, 319
Percy, J., on copper, 708
Perlich, R. W., analyses by, 220
Perry, E. S., and Cooke, S. R. B., on beryl, 309
on fergusonite, 314
Perthite, 174
Peru, Geological explanation of geophysical anomalies near Cerro de Pasco (Kruger and Lacy), 485
Peterson, N. P., on Mammoth area, Ariz., 254
on Tornado Peak, Ariz., 25
Petreck, A. J., on torbanite, 70
Petrofabric analysis (review), 156
Petrographic analysis of coal by the particle count method (Parks), 376
Petroleum (reviews), 242, 628
Middle East (review), 351
North America (review), 629
property valuation (review), 459
United States, consumption, 162
structure of fields (review), 155
Petrology, textbook (review), 457
Pettijohn, F. J., reviews of book by, 243, 745
Phillips, A. H., analysis by, 220
Phosphate, Paikungshan coal field, China, 141
Photomicrographs—
chromite, New Caledonia, 529, 537
coal, (facing), 382, 618
minerals of pegmatites, Mont., 316
ores, copper, Butte, Mont., (facing), 472, 478
polishing sequence, 123
San Manuel, Ariz., (facing), 266
silver, (facing), 440
quartz, (facing), 94
rocks, Coeur d'Alene district, Idaho, (facing), 182
Venencocha area, Peru, 489
tourmaline, 189
Phyteral, 5, 494
Pickering, W. Y., and Dorn, C. L., oil, Rangely field, Colo. (review), 155
Pickett, E. E., spectroscopic analysis by, 452
Pipes, copper ore, Ab Swayel mine, Egypt, 145, 147
Piroutet, M., on geology, New Caledonia, 526
Placer deposits, Logarithmic pattern in river (Wertz), 193
Plagioclase, 173
Plans, Ab Swayel mine, Egypt, 145
Friends, Station, zinc deposit, Tenn., 288
pegmatites, Montana, 312
Seventy Nine mine, Ariz., 30
Plant microfossils, 495
Plants, geochemical prospecting, 709
Plastics for mineral mounts, 472
Poland, J. F., title by, 84
Polishing sections of ores, A method for (Sampson), 119
Pollard, W. B., analysis by, 144
Posepny, F., on crustification, 87
Posnjak, E., Allen, E. T., and Merwin, H. E., on sulphides, 476
Powers, F. D., on chromite, 527
Prospecting for ores: A progress report, Geochemical (Hawkes), 706; abstract, 80
Proustite, 678
Pseudomorphs, goethite after pyrite, 488
Pumpellyite, 488, 490
Pyrite, 81, 90, 176, 266, 281, 320, 388, 430, 474, 488, 571, 676, 681
Seventy Nine mine, Ariz., 33
Pyrometasomatic ore deposits, 237
Pyroxene, 173
Pyrrhotite, 331, 333

Quartz, 15, 89, 175, 188, 320, 326, 468, 488, 561, 572, 602, 676, 688, 725, 729
Origin of the Bendigo saddle reefs with comments on the formation of ribbon (Chace), 561

Quartz veins, Ribbon structure in gold- (McKinstry and Ohle), 87
Quebec, Aeromagnetic survey of the Allard Lake district (Bourret), 732

Raguin, E., review of book by, 628
Ramberg, H., discussion by, 551
Ramdohr, P., on magnetite, 221
  review of book by, 351
Rankama, K., on nickel, 709
  on prospecting, 707
Ransome, F. L., on Banner district, Ariz., 25
  on book structure, 91
  on Goldfield area, Nev., 455
  on porphyry, 274
  on ribbon structure, 562
  on Wallapai district, Ariz., 664
Ransome, F. L., and Calkins, F. C., on monzonite, 171
Rastall, R. H., on granites, 337
Ratsbaum, E. A., on spectrographs, 709
Ray, J. C., on textures, 472
Read, H. H., on kyanite, 318
Reagents for zinc tests, 297
Reefs with comments on the formation of ribbon quartz, Origin of the Bendigo saddle (Chace), 561
Rees, O. W., Wagner, W. F., and Tilbury, W. G., on coal, 7
Reflectivity of the ore minerals, Determination of (Folinsbee), 425
Reichen, L., analyses by, 292
Reichen, L. E., and Lakin, H. W., on vegetation, 709
Reid, A. M., on zoning, 239
Reid, J. A., on metallogenetic provinces, 338
Reinsch, P. F., on *Triletes*, 498
Reissinger, A., on plants, 495
Replacement, book structure, 92
  copper minerals (abstract), 642
  quartz bodies, Bendigo, Australia, 83, 581
  Seventy Nine mine, Ariz., 33
  silver ores, Gowganda, Ont., 440
Research and study, Coal geology: An opportunity for (Cady), 1
Research in coal paleobotany since 1943 (Schopf), 492
Research in the natural history of coal beds, Sedimentation: An appropriate field of (Dapples), 598
Reserves, coal, United States, 164
Retty, J. A., on Allard Lake district, Quebec, 732
  on Morin Series, Que., 734
Reviews—
  Arabian oil. America's stake in the Middle East (Mikesell and Chenery), Leighton, 351
  Bergwerk- und Probierbüchlein (on mining geology and assaying), (Sisco and Smith), Bateman, 745
Reviews—Continued
  Bergwirtschaft der Erde, 4th edit. (Friedensburg), 243
  Cobalt (Young), 73
  College geography, 3rd edition (Chase and Bergsmark), 556
  Contribution to the published information on the geology and ore deposits of Goldfield, Nevada (Searls), Ferguson, 455
  Dana's minerals and how to study them (Dana and Hurlbut), 242
  Domestic mining industry of the United States in World War II (Morgan), 629
  Ellenburger Group of central Texas (Cloud and Barnes), 555
  Emanuel Kayser's Abriss der Geologie. Part II, Historical geology (Brinkmann), 555
  Examination and valuation of mineral property, 3rd edition (Parks), 459
  Geologia della miniera di Montevecchio (Cavinato and Zuffardi), Mignone, 555
  Geologic guidebook along Highway 49 (Jenkins), Wells, 74
  Géologie des gites minéraux (Raguin), Mignone, 628
  Geology and man (Landes and Hussey), 352
  Gesteine und Minerallagerstätten. Bd. I. Allgemeine Lehre von den Gesteinen und Minerallagerstätten (Niggli), Knopf, 457
  Grundwasserkunde, 2nd edit. (Koehne), 458
  Heat conduction with engineering and geological applications (Ingersoll, Zobel, and Ingersoll), 352
  Historical geology (Dunbar), 243
  Hydrology (Wisler and Brater), 746
  Klockmann's Lehrbuch der Mineralogie, 3rd edit. (Ramdohr), 351
  Landscape, as developed by the processes of normal erosion, 2nd edit. (Cotton), 630
  Lo stagno (Bonetti), Mignone, 629
  Mineralogical and structural evolution of metamorphic rocks (Turner), 155
  Mines Register, successor to Mines Handbook, Vol. 23, 746
  Mining geology (McKinstry), Davidson, 347
  Oil fields in North America (Ver Wiebe), 629
  Ore genesis: A metallurgical interpretation (Brown), Noble, 554
  Physical geology, 3rd edit. (Longwell, Knopf, and Flint), 72
  Physical geology and man (Landes), 352
  Principles of petroleum geology (Lalicker), 242
  Sedimentary rocks (Pettijohn), 243, review by Leighton, 745

Reviews—Continued
Structural geology of Canadian ore deposits—A symposium (Wilson *et al.*), Bateman, 72
Structure of typical American oil fields, Vol. III (Howell *et al.*), 155
Submarine geology (Shepard), 73
Subsurface geologic methods—A symposium (LeRoy and Crain), 746
Revsdinskite, 22
Rhodochrosite, 478
Ribbon quartz, Origin of the Bendigo saddle reefs with comments on the formation of (Chace), 561
Ribbon structure in gold-quartz veins (McKinstry and Ohle), 87
Richards, —., analysis by, 219
Rickard, T. A., on Bendigo goldfield, Australia, 568
on slag, 149
Riddle, Oregon, Variations in garnierite from the nickel deposit near (Pecora, Hobbs, and Murata), 13
Riebeckite, 190
Ries, H., communication by, 741
Ripple marks, 197
River placer deposits, Logarithmic pattern in (Wertz), 193
Roberts, J. K., and Collins, R. L., on Holly Springs formation, Tenn., 622
Robinson, A. H. A., on ilmenite, 228
Robinson, W. O., on quartz, 297
Robinson, W. O., Lakin, H. W., and Reichen, L. A., on zinc, 709
Rocks, Arizona, Wallapai district, 666
igneous rocks, accessory minerals, paragenesis (abstract), 642
metamorphic rocks, mineralogy and structure (review), 155
sedimentary rocks (reviews), 243, 745
Rocks and mineral deposits (review), 457
Roe, B. R., abstract by, 644
Rogers, A. F., on baddeleyite, 315
on textures, 472
Rokhlin, M. I., on tin, 708
Rosin, P., and Rammler, E., on coal, 406
Rosin and Rammler Law, 406
Ross, C. P., on Banner district, Ariz., 25
on dikes and sills, 28
on metamorphism, 309
Ross, C. S., and Kerr, P. F., on nacrite, 687
Ross, C. S., Shannon, E. V., and Gonyer, F. A., on genthite, 22
Rossi, —., analysis by, 220
Rutile, 266, 699

Safflorite, 442
Sahama, T. G., on sphene, 687
Sahinen, U. S., on pegmatites, 309
Sahni, B., on plant fossils, 495
Sales, R. H., on Butte ore deposits, Mont., 468
on fissures, 692
on mineral exploration, 545
Sales, R. H., and Meyer, C., *Results from preliminary studies of vein formation at Butte, Montana,* 465–484
on Butte veins, Mont., 466
on dickite, 687
Sampling, coal for petrographic analysis, 384, 389
ores and rocks (review), 348
soils for zinc, 291, 301
Sampson, E., *A method for polishing sections of ores,* 119–127
on serpentinite, 540
Sandell, E. B., on dithizone, 297, 342
Sands, examination (communication), 741
Sands from New Jersey, Some glass (Wilkerson and Comeforo), 63
Sandstones, 602
Sanidine, 331, 333
Saponite, 20, 534
Saudi Arabia, oil (review), 351
Saxonite, 15
Sayre, A. N., abstract by, 638
memorial by, 248
Schaefer, E. J., White, G. W., and Van Tuyl, D. W., on a buried valley, 514
Schmedeman, O. C., on dickite, 687
Schmitt, H., abstracts by, 80, 641
on mining geology, 546
Schneider, R., *A hypothesis on the origin of a limonitic layer in beds of Eocene age in Fayette County, Tennessee,* 621–623
Schneiderhöhn, H., and Ramdohr, P., on light filters, 429
on reflectivity, 431
Schopf, J. M., *Cannel, boghead, torbanite, oil shale,* 68–71
Research in coal paleobotany since 1943, 492–513
on incoalation, 5
on plant materials, 493
on spores, 498
on waxes, 658
Schopf, J. M., Wilson, L. R., and Bentall, R., on spores, 497
Schrader, F. C., on Wallapai district, Ariz., 664
Schrauth, W., on lignin, 656
Schwartz, C. B., petroleum, Fouke field, Ark. (review), 155
Schwartz, G. M., *Oxidation and enrichment in the San Manuel copper deposit, Arizona,* 253–277
abstracts by, 81, 253
on alteration, 686
on chalcocite, 271
on chalcopyrite, 677
on San Manuel area, Ariz., 254
on textures, 267, 482
Schwerin, M., on fluorite, 606
Scientific Notes and News, 85, 159, 250, 356, 463, 559, 647, 750
Scofield, C. S., on water, 59
Scorodite, 681
Scotland, spore studies, 499

Scott, E. R., oil, Quitman field, Texas (review), 155
Scott, H. S., on decrepitation, 449
Scrivenor, J. B., on monazite, 235
Seager, G. F., on pegmatites, 311
Searls, F., Jr., review of bulletin by, 455
Sebelien, J., analyses by, 144
Sections—
Azapa valley, Chile, 51
Bendigo saddle reefs, Australia, 563
fluorite deposits, Ill., 608
Huainan Basin, China, 132
Pennsylvanian cyclothem, 603
San Manuel copper deposit, Ariz., 258
Seventy Nine mine, Ariz., 31, 34
soil, definitions, 287
stratigraphy, Paikungshan coal field, China, 138
Venencocha area, Peru, 487
zinc deposit, Friends Station, Tenn., 289
Sections of ores, A method for polishing (Sampson), 119
Sedimentary rocks (reviews), 243, 745
Sedimentation, limonite, Fayette Co., Tenn., 621
placer deposits, 193
Sedimentation: An appropriate field of research in the natural history of coal beds (Dapples), 598
Selenite, 683
Selfridge, G. C., on hydrosilicates, 22
Selling, O. H., on spores, 498, 508
Sergeev, E. A., on copper, 708
on geochemical prospecting, 707
Sergeev, E., and Solovov, A., on copper, 708
Sericite, 176, 181, 324, 591
Sericitization, 181
Butte, Mont., 474, 477
Serpentine, 20, 525, 536
Serpentinization, 542
Seventy Nine mine, Gila County, Arizona, Structural control and mineralization at the (Kiersch), 24
Seyler, C. A., on coal, 619, 659
Shales, 602
Shand, S. J., on andesite, 339
Sheet structure, a major factor in the occurrence of ground water in the granites of Georgia (LeGrand), 110
Shenon, P. J., and McConnel, R. H., on Coeur d'Alene district, Idaho, 171
Shepard, F. P., review of book by, 73
Short, M. N., on microchemistry, 710
on ore briquets, 276
on ore minerals, 425
Short, M. N., *et al.*, on diabase, 28
Siderite, 137, 142, 679
Silicate systems, immiscibility (discussion), 742
Sillimanite, 316, 318
Sills, Seventy Nine mine, Ariz., 28
Wallapai district, Arizona, 667
Silver, calculator for values, 445
England, Dartmoor granite, 338
Nevada, Goldfield area (review), 455
Seventy Nine mine, Ariz., 36
Wallapai district, Ariz., 678, 683
Washington, Northport district (abstract), 639
Silver at Gowganda, Ontario, Deposition and resolution of native (Bastin), 437
Simpson, E. S., *Buried preglacial ground water channels in the Albany-Schenectady area in New York*, 713–720
Sims, P. K., Payne, J. N., and Cady, G. H., on Herrin coal, Ill., 604
Singewald, J. T., Jr., on chromite sands, 540
Sisco, A. G., and Smith, C. S., review of translations by, 745
Sketchmaster for making geologic maps (communications), 551
Skutterudite, 442
Slags, analysis, Ab Swayel mine, Egypt, 144
Slickensides, 89, 567, 593
Smith, C. H., books received, 747
Smith, F. G., *Transport and deposition of the non-sulphide vein materials. IV. Tourmaline*, 186–192
communication by, 624
discussion by, 741
discussion of papers by, 151, 551
on a pressure vessel, 187
on solutions, 721
on tourmaline, 730
on ziroconium oxide, 730
Smith, F. G., and Peach, P. A., communication by, 449
Smith, H. T. U., on photogrammetric methods, 553
Smith, R. C., and Howard, H. C., on humic acids, 651
Sohn, I. G., communication by, 551
Soils, Field method for the determination of zinc in (Lakin, Stevens, and Almond), 296
geochemical prospecting, 708
Jefferson Co., Tenn., 290
Soils and weathering, 287
Sokoloff, V. P., on prospecting, 707
Sorenson, R. E., on bleached zones, 180
on Coeur d'Alene district, Idaho, 171
South America, Mines Register (review), 746
Spaenhauer, F., on kyanite, 318
Spangenberg, K., on hydrosilicates, 22
Specific gravity, coal, 415
Spectroscopy, geochemical prospecting, 709
tree ash, 452
vein ores (abstract), 642
Sphalerite, 239, 287, 469, 607, 677, 682, 698
Sphene, 175, 323, 685, 687
Spines, bornite, Butte, Mont., 474
Spores, literature, 497

Springs, Azapa valley, Chile, 56
granite terranes, Ga., 118
thermal springs and prospecting (abstract), 83
Sprunk, G. C., on phyterals, 8
Sprunk, G. C., and O'Donnell, H. J., on coal, 389
Spurr, J. E., on dikes, 695
on veins, 456
Stadnikov, G., and Titov, N. G., on bitumens, 658
Staker, E. V., and Cummings, R. W., on zinc, 708
Steele, H. J., and Rubly, G. R., on San Manuel prospect, Ariz., 254
Steiger, G, analysis by, 220
Stenzel, H. B., abstract by, 638
Stephenson, H. K., on chromite, 540
Sterrett, D. B., on mica, 308
on turquoise, 700
Stevens, R. E., with Lakin, H. W., and Almond, H., *Field method for the determination of zinc in soils*, 296–306
Stewart, J. S., petroleum, Norman Wells field, N.W.T. (review), 155
Stibnite, 679
Stiles, W., on trace analysis, 304
Stillwell, F. L., on Bendigo goldfield, Australia, 568
on laminae, 94
on quartz, 575, 582
on replacement, 100
Stillwell, F. L., and Edwards, A. B., on porphyry, 238
Stockley, G. M., on titanomagnetite, 228
Stoll, W. C., on pegmatites, 309
Stoller, J. H., on buried channels, 717
Stone, J. B., on Bendigo goldfield, Australia, 568
on ore, 343
on ribbon structure, 105
Stopes, M. C., on coal, 5, 379
Stoping values from assays of narrow veins, A device for calculating (Kruger), 445
Storage at Canton, Ohio, The utilization of induced stream infiltration and natural aquifer (Kazmann), 514
Stratigraphy, Adirondack Mtns., N. Y., 211
Azapa valley, Chile, 40, 48
Eocene, Fayette Co., Tenn., 621
New Caledonia, 526
Paikungshan coal field, China, 137
Seventy Nine mine, Ariz., 28
Shelby district, Ala., 281
subsurface methods (review), 746
Stream infiltration and natural aquifer storage at Canton, Ohio, The utilization of induced (Kazmann), 514; abstract, 84
Structural control and mineralization at the Seventy Nine mine, Gila County, Arizona (Kiersch), 24
Structure, a major factor in the occurrence of ground water in the granites of Georgia, Sheet (LeGrand), 110
Arizona, Wallapai district, 668
Butte dome, Mont., 469
domes and ore deposits, 343
Huainan Basin, China, 130
metamorphic rocks (review), 155
oil fields, U. S. (review), 155
ore deposits, Canada (review), 72
San Manuel area, Ariz., 256
Shelby district, Ala., 281
subsurface methods (review), 746
Structure in gold-quartz veins, Ribbon (McKinstry and Ohle), 87
Structures due to volume shrinkage in the bedding-replacement fluorspar deposits of southern Illinois (Grogan), 606
Stuckey, J. L., on kyanite, 318
Stylolites, 99
Submarine geology (review), 73
Subsurface geologic methods (review), 746
Sullivan, C. J., discussion of his paper by, 336
discussions of papers by, 234, 625
on dikes, 341
on tantalum, 235
Sulphides, California, Iron Mtn. deposits (abstract), 81
replacement, 592
Sulphur in mineralization, 478
Sulphur ratio, 478
Sundaland granites, 239, 240
Survey of the Allard Lake district, Quebec, Aeromagnetic (Bourret), 732
Swesnik, R. M., oil, West Edmond field, Okla. (review), 155
Synthesis, chalcocite, 483
petroleum products from coal, 163
tourmaline, 186
zircon, 721
Systems, hydrous silicates (discussion), 742

Taber, S., on ribbon structure, 92, 562
Tables, analyses, garnierite, Oregon, 16
rocks and ores, Adirondacks, 219
tree ash, 452
borings, Paikungshan coal field, China, 135, 139
flow of Nimishillen Creek, Ohio, 519
coal, banded ingredients, 380
coal reserves, U. S., 167
glass sands, N. J., 65
gold and silver in granite, 338
lithologic associations, 602
mineral production, Cerbat Range, Ariz., 672
nickel in implements, Egypt, 144
ore minerals, reflectivity, 427
ores, geochemical prospecting, 708
stratigraphy, Azapa valley, Chile, 48
Eocene, Fayette Co., Tenn., 621
tourmaline, 188
zinc, field tests, 302

Tables—Continued
zinc content of soil, Tenn., 290
zirconium minerals, stability, 723
Tansley, W., Schafer, P. A., and Hart, L. H., on pegmatites, 309
Tantalum, 235, 336
Tasmania, tin, zoned deposits (discussion), 238
Taylor, E. M., on coal, 657
Taylor, G. C., Jr., *Geology and ground water of the Azapa valley, Province of Tarapacá, Chile*, 40–62
Technique, aeromagnetic survey, Allard Lake, Que., 737
alluvial trough, 193
analysis for geochemical prospecting, 709
apparatus for mineral decrepitation, 449
calculator for stoping values, 445
copper ore study, 273, 276
electron microscopy, coal, 617
glass sand testing, 64
magnetic properties of chromite, 540
petrographic analysis of coal, 377, 389
plastics for mineral mounts, 472
polished and thin section preparation, 370
polishing sections of ores, 119
reflection apparatus for ores, 425
sampling soils for zinc, 291
sketchmaster, 551
stability experiments, zirconium minerals, 722
subsurface methods (review), 746
tests for pneumatolytic ores, 624
tests for zinc, 297
vein trend determination, 672
Tectonic control of sedimentation, 600
"Telescoped" ore deposits, tin, Tasmania (discussion), 238
"Telescoped" pegmatites, Mont., 332
Tennantite, 476, 678
Tennessee, A hypothesis on the origin of a limonitic layer in beds of Eocene age in Fayette County (Schneider), 621
Vestigial zinc in surface residuum associated with primary zinc ore in east (Hawkes and Lakin), 286
Terres, E., on nitrogen, 657
Tetrahedrite, 678
Texas, coal (abstract), 638
Ellenburger Group (review), 555
ground water, El Paso region (abstract), 638
mercury, Terlingua district (abstract), 640
Textures, copper-iron-sulphur minerals, 472
Thayer, T. P., on chromite, 542
Thermal analysis, garnierite, 20
Thermal springs and ore prospecting (abstract), 83
Thiessen, R., on anthraxylon, 4
on torbanite, 68
Thiessen, R., and Sprunk, G. C., on anthraxylon, 4
Thiessen, R., and Wilson, F. E., on fusain, 6
Thomas, B. E., *Ore deposits of the Wallapai district, Arizona*, 663–705
Thompson, G. A., with White, D. E., and Brannock, W. W., abstract by, 83
Thomson, J. E., on silver ores, 438
Thorium, 235, 336
Thyssen, S. V., on prospecting, 707
Tikhomirov, N. I., and Miller, S. D., on copper, 708
Tin, 336; (review), 629
England, Cornwall, 624
transportation and deposition, 191
Titaniferous magmas, The differentiation of (Evrard), 210
Titanomagnetite, 225
Todd, E. W., on silver, 440
Tolman, C. F., on metacolloid texture, 271
Torbanite, oil shale, Cannel, boghead, (Schopf), 68
Tourmaline, 320, 326
Transport and deposition of the non-sulphide vein minerals. IV. (Smith), 186
Transport, minerals, non-sulphide pegmatitic, 151
Transport and deposition of the non-sulphide vein minerals. V. Zirconium minerals (Maurice), 721
Transport of pegmatite minerals (discussions), 551, 741
Trees, alumina content over clay pits, 451
Tremolite, 333
Triletes, 498, 508
Tungsten, Arizona, Helvetia district (abstract), 640
California, Bishop district (abstract), 79
Turner, F. J., review of book by, 155
Turner, H. G., on anthracite, 657
Turquoise, Wallapai district, Ariz., 663, 700
Tuttle, O. F., and Friedman, I., on liquid immiscibility, 742
Twelvetrees, W. H., on zoning, 239
Twelvetrees, W. H., and Ward, L. K., on Heemskirk-Zeehan district, Tasmania, 239

Umpleby, J. B., and Jones, E. L., Jr., on ore, 183
Underground water (review), 458
California, Los Angeles Co. (by title), 84
geochemical prospecting, 708
hydrology (review), 746
Idaho, Cache valley (by title), 84
Ohio, Canton, stream infiltration (abstract), 84
Texas, El Paso region (abstract), 638
Uniformitarianism and ideal vein (abstract), 80
Union South Africa, torbanite, 69
U.S.S.R., spore studies, 497

U. S. Bur. Mines, exploration for ore deposits, 373
U. S. Geol. Survey, exploration for ore deposits, 372
United States, coal and lignite (abstracts), 643, 645, 646
fuel supplies, 161
lignites, petography (abstract), 645
limestone, metallurgical reserves (abstract), 641
map (review), 458
mineral law and taxation, 373
mineral resources (abstract), 82
Mines Register (review), 746
mining industry in World War II (review), 629
petroleum (review), 629
structure of fields (review), 155
Utilization of induced stream infiltration and natural aquifer storage at Canton, Ohio (Kazmann), 514

Vanderwilt, J. W., on polishing ores, 119
Van Tuyl, D. W., on stream flow, 523
Variance, zinc field tests, 304
Vein formation at Butte, Montana, Results from preliminary studies of (Sales and Meyer), 465
Vein minerals. IV. Tourmaline, Transport and deposition of the non-sulphide (Smith), 186
V. Zirconium minerals, Transport and deposition of the non-sulphide (Maurice), 721
Veins, A device for calculating stoping values from assays of narrow (Kruger), 445
Ribbon structure in gold-quartz (McKinstry and Ohle), 87
Arkansas, Ouachita mineral province (abstract), 79
chemistry and spectroscopy (abstract), 642
Coeur d'Alene, Idaho, 181
minerals, transport and deposition, 151; (discussions), 551, 741
Nevada, Goldfield area (review), 455
pegmatites, Montana, 307
silver, Gowganda, Ont., 438
uniformitarianism and ideal vein (abstract), 80
Wallapai district, Arizona, 663, 671
Verhoogen, J., on titanomagnetite, 225
Vermiculite, Libby, Mont., 333
Vermont, lignite, Brandon (abstract), 645
Ver Wiebe, W. A., review of book by, 629
Violarite, Egypt, 147
Virkki, C., on spores, 504
Vitrain, 379, 398
Vogt, T., on copper, 709
Vogt, T., and Bergh, H., on metals, 708
Vogt, T., and Bugge, H., on plants, 709
Vogt, T., and Rosenqvist, A. M., on water, 709
Vogt, T., Braadlie, O., and Berg, H., on plants, 709
Von Foullon, H. B., on Riddle district, Ore., 14
Vugs, 17, 96, 320, 323, 572, 690

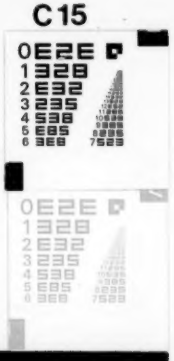
Waksman, S. A., on humus, 651
Waksman, S. A., and Stevens, K. R., on lignin, 653
Waldschmidt, W. A., petroleum, Gramp's field, Colo. (review), 155
Wallapai district, Arizona, Ore deposits of the (Thomas), 663
Walters, R. F., and Price, A. S., oil, Kraft-Prusa field, Kan. (review), 155
Wanless, H. R., on isopach maps, 598
Ward, L. K., on Heemskirk-Zeehan district, Tasmania, 239
Warren, C. H., on ilmenite, 227
Warren, H. V., and Delavault, R. E., on plants, 709
Warren, H. V., and Howatson, C. H., on plants, 709
Washburn, E., on system ZrO_2—SiO_2, 727
Washington, ore deposits, Northport district (abstract), 639
Wasson, T., oil, Creole field, La. (review), 155
Water, surface water, geochemical prospecting, 709
Water in the granites of Georgia, Sheet structure, a major factor in the occurrence of ground (LeGrand), 110
Water of the Azapa valley, Province of Tarapaca, Chile, Geology and ground (Taylor), 40
Waterhouse, L. L., on cassiterite, 238
Weathering, garnierite, Riddle, Ore., 15
granites, Georgia, 111
Weathering and soils, 287
Weed, W. H., on pegmatites, 309
Weeks, L. G., on Cretaceous, Tarapacá Province, Chile, 45
Weiler, J. F., on coal, 5, 652, 653
Wells, F. G., review by, 74
Wells, Azapa valley, Chile, 51
water, Canton, Ohio, 517
granite terranes, Ga., 117
Wendlandt, E. A., and Shelby, T. H., Jr., oil, Talco field, Texas (review), 155
Wertz, J. B., *Logarithmic pattern in river placer deposits*, 193–209
White, C. D., on torbanite, 68
White, D. E., Thompson, G. A., and Brannock, W. W., abstract by, 83
Whitehead, W. L., oil, property valuation (review), 459
Whitlatch, G. I., on Eocene stratigraphy, Tenn., 621
Wicher, C. A., on spores, 509
Wilkerson, A. S., and Comeforo, J. E., *Some glass sands from New Jersey*, 63–67
on glass sands, 63

Williams, R. C., and Wyckoff, R. W. G., on metal-shadowing technique, 619
Willman, A., analyses by, 220
Willstatter, R., and Kalb, L., on lignin, 656
Wilson, H. S., on slickensides, 90
Wilson, L. R., on spores, 510
Winchell, A. N., on carbon dioxide, 330
on pegmatites, 309
on silicates, 727
Wisler, C. O., and Brater, E. F., review of book by, 746
Wisser, E., discussion of paper by, 233
on gouge, 693
Woodworth, J. B., on Lake Albany, N. Y., 716
Wooster, W. A., on coal, 659, 660
Wyckoff, R. D., on magnetometers, 736

X-ray photographs, violarite, Egypt, 147
zirconium minerals, 726
X-ray study, garnierite, 20
tourmaline, 187
zirconium minerals, 724

Yates, R. G., and Thompson, G. A., abstract by, 640
Young, R. S., review of book by, 73

Zealley, A. E. V., on chromite, 540
Zinc, Arizona, Helvetia district (abstract), 640
Seventy Nine mine, Ariz., 36
Wallapai district, 663
California, Iron Mtn. (abstract), 82
Italy, Montevecchio (review), 555
Mexico (abstract), 639
Pachuca district (discussion), 233
Washington, Northport district (abstract), 639
Zinc in soils, Field method for the determination of (Lakin, Stevens, and Almond), 296
Zinc in surface residuum associated with primary zinc ore in east Tennessee, Vestigial (Hawkes and Lakin), 286
Zircon, 176, 721
Zirconium minerals, Transport and deposition of the non-sulphide vein minerals. V. (Maurice), 721
Zoisite, 488
Zoning, microcline crystals, 174
sulphide minerals, Butte, Mont., 468
tin, Tasmania (discussion), 238
Wallapai district, Ariz., 692
Zunyite, 490


C15